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Stratigraphy and Depositional Environment of the Middle Atoka Formation, Central Arkoma Basin, Western Arkansas

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Stratigraphy and Depositional Environment of the Middle Atoka Formation, Central Arkoma
Basin, Western Arkansas

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Geology

by

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China University of Petroleum
Bachelor of Engineering in Resource Exploration, 2013

December 2016
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This thesis is approved for recommendation to the Graduate Council.

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ABSTRACT

Wire line logs are widely used in analysis of the subsurface stratigraphy of the middle Atoka Formation, Central Arkoma Basin, Western Arkansas. SP log, Gamma ray log, resistivity log and conductivity log provide valuable information to construct cross sections.

The middle Atoka formation is composed of a succession of shale and sandstone alternations with thickness reaching approximately 3000 feet in the study area. It contains several sandstone units which include Morris, Tackett, Areci, Bynum, Casey and Dunn”A” separated by shale intervals. The purpose of this study is to identify these units and predict sequence stratigraphy and depositional environment by constructing cross-sections, observing wireline logs and associating previous research. Several isopach maps are made, explaining the development of sandstone in target units such as Tackett and Casey.

The sequence stratigraphy of the middle Atoka formation is mainly composed of transgressive systems tracts and part of a highstands systems tract. The intervals indicate successive sea-level cycles associated transgression and regression from shallow marine to shoreface.

The middle Atoka formation has been proved as a significant exploration target since 1950’s. In order to understand geologic setting and find potential reservoirs within the Arkoma basin, it is vital to comprehend the sequence development and depositional environment of the intervals within the middle Atoka.

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1. INTRODUCTION

1.1 Geological Setting

1.1.1 Arkoma Basin

The Arkoma Basin is a peripheral foreland basin (Allen et al., 1986; Miall, 1995; Griles, 1996) bounded by the Choctaw fault and Ross creek fault on the south side, by the Ozark uplift and northeast Oklahoma platform on the north side, by Seminole uplift, the Arbuckle mountains on the western side and by Cenozoic coastal plain on the eastern side (Figure 1). It ranges 40-80 km wide.

The Arkoma Basin is the most northern, least deformed, and youngest part of a northward-migrating foreland basin that began forming in the early Mississippian. The formation of this basin was caused by the collision of North American and Sabine Terrane plate from the early Mississippian to the Middle Pennsylvanian time. The Ouachita fold and thrust belt has a close relationship with the sedimentary and structure of Arkoma Basin (Suneson, 2012).



Figure 1 Outline of the Arkoma basin, the study area is indicated by the black square

Chesterian, Morrowan, and early Atokan time were stable periods for the Arkoma Basin.

After that, the syndepositional faults caused by continued basin subsidence widely developed during middle Atokan time (Figure 2). The basin is characterized by increasing thickness from north to south (Sutherland, 1988). This process is a significant mark which Arkoma Basin was transited from a passive margin to a foreland basin.

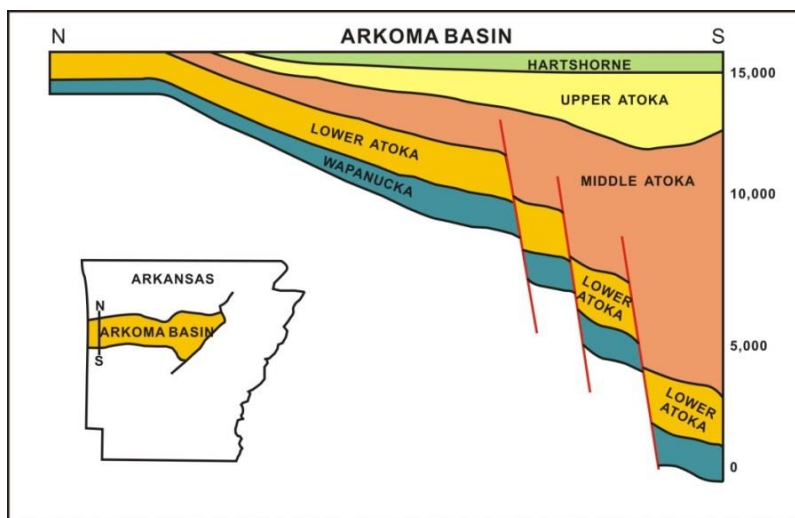


Figure 2 North-south section across Arkoma basin showing syndepositional faults (modified from Zachry and Sutherland, 1984)

1.1.2 Ozark Dome

The Ozark Dome is a highland region of approximately 150,000 km² known as Ozark uplift, Ozark Mountains or Ozark Plateau. It is an asymmetrical, broad and extended uplift which covers south part of Missouri, northern part of Arkansas and northeastern part of Oklahoma (Figure 3). Its northern boundary is located near the Missouri River. Its southern boundary goes across from Batesville on the east to Fayetteville on the western. The eastern boundary lies on the Mississippi River and the western ends in northeastern Oklahoma.

Stratigraphic data indicates that in the Mississippian Period it was submerged in shallow marine environment. After that, it was uplifted caused by the Ouachita orogeny in Pennsylvanian Period. The deep ocean basin was lifted due to the collision between the Sabine Plate and denser North American continental crust. It rose a few hundred meters by the end of Paleozoic.

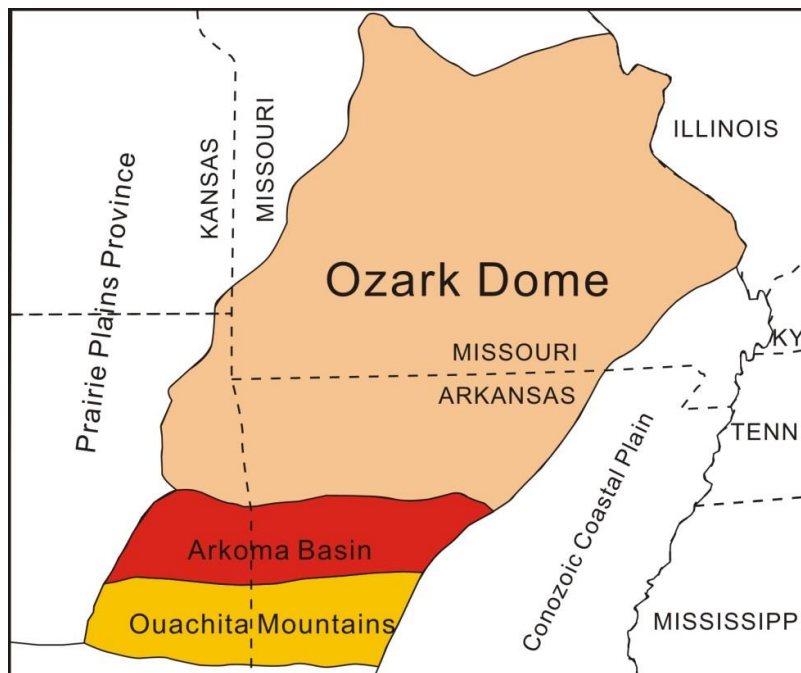


Figure 3 Map of Ozark Dome (modified from Huffman, 1958)

1.1.3 Ouachita Mountain Fold Belt

The Ouachita fold belt trends east across Arkansas and eastern Oklahoma. The boundary to the north is the Choctaw fault and the southern boundary is the Cretaceous overlap. It ranges from 80 km to 96 km wide in Arkansas and extends 180 km from the eastern to western.

Deformation of the Ouachita fold belt was due to the interaction of North America and the Sabine micro plate. The evidence shows that the thickness of southward Carboniferous sequence increases to an Atlantic style continental margin. The lack of Paleozoic plutonic rocks and high-temperature low-pressure metamorphic rock also proves that the Ouachita Mountain is remnant of an antithetic subduction zone (Roeder, 1973).

The Ouachita orogeny activity happened during Late Pennsylvanian to the Permian Time (King, 1961; Denison et al, 1969). Outcrops from the Ouachita Mountains includes a series of deep water chert, shale, submarine debris flows, and turbidite sandstone from Cambrian to lower Mississippian and another outcrops above them is flysch (Ann et al, 1988).

1.2 Study Area

The portion of the Arkoma basin included in this study is limited to west-central Arkansas. The study area includes Townships 7-9 North and Ranges 27-30 West. It encompasses approximately 507 square miles and includes southeastern Crawford, northeastern of Sebastian and western Franklin counties (Figure 4).

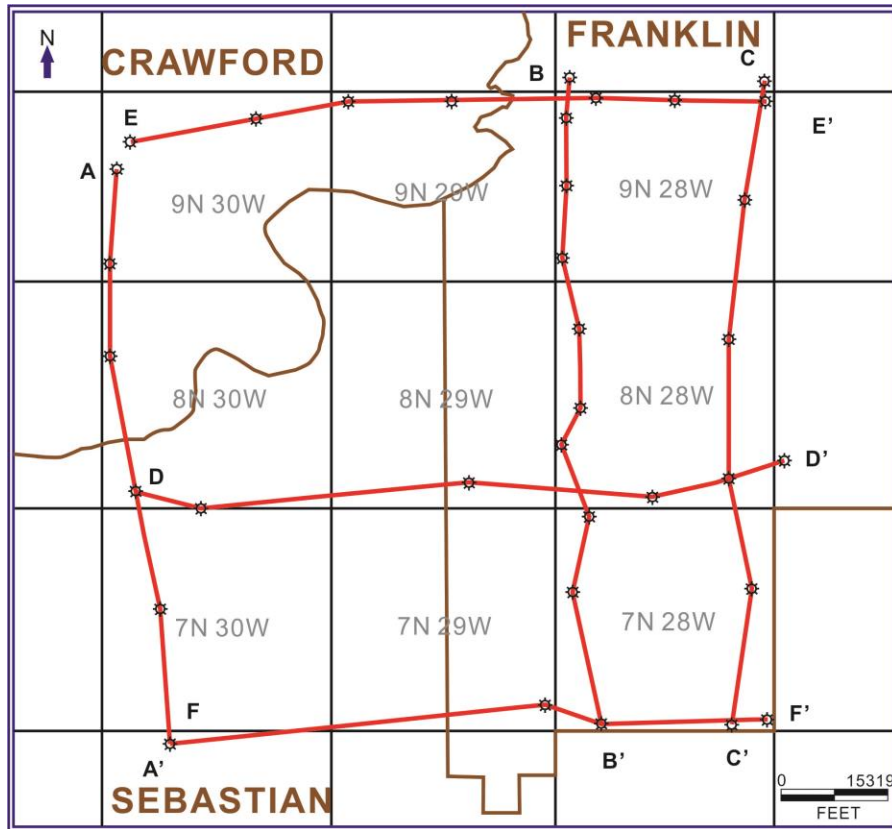


Figure 4 Location of study area. Cross sections and wells are shown on the map.

1.3 Lithostratigraphy

The Atoka formation is composed of shales and sandstones that display complex stratigraphic and facies characteristics (Figure 5). The maximum thickness of Atoka formation is approximately 6,400 m along the southern margin of the basin (Haley, 1982). The minimum thickness ranges from 305 m to 396 m from northern margin of the Arkoma basin (Zachry, 1983). The Atoka formation can be included to upper, middle and lower member (Johnson, 1968; Zachry, 1983).

The middle Atoka formation in Arkansas composes mainly shale, but with a great number

of sandstone intervals. For example, there are four to eight sandstone units with thickness exceeding 15 feet that occur south of 7 N. The grain size profiles suggest that sandstone were formed at the distal margin of active submarine-fan systems (Zachry and Sutherland, 1984).

The units' names are from the stratigraphic column are on the basis of petroleum industry. Other used names are showed in the table 1. The middle Atoka fomation includes Morris, Tackett, Areci, Bynum and Casey (Figure 5).

System	Series	Formation	Sandstone Unite	Other used name	
PENNSYLVANIAN	ATOKAN	ATOKA	UPPER	UPPER CARPENTER	CARPERNTER A
				UPPER ALMA	
				MANSFIELD	
				MIDDLE ALMA	
				LOWER ALMA	
				LOWER CARPENTER	CARPENTER B
			MIDDLE	MORRIS	SELF, TACKEET
				TACKETT	WOOLSEY, MORRIS
				ARECI	SELF
				BYNUM	HOOD
				CASEY	HUDSON 1
			LOWER	SELLS	DUNN A
				UPPER JENKINS	RALPH BARTON, UPPER ALLEN, JENKINS
				LOWER JENKINS	DUNN B
				DUNN C	DAWSON, DAWSON A, ALLEN
				CECIL SPRIO	CECIL, HAMM
				SPIRO	ORR

Table 1 Stratigraphic column depicting from Atokan (Haley and Hendricks, 1972; Zachry, 1983)

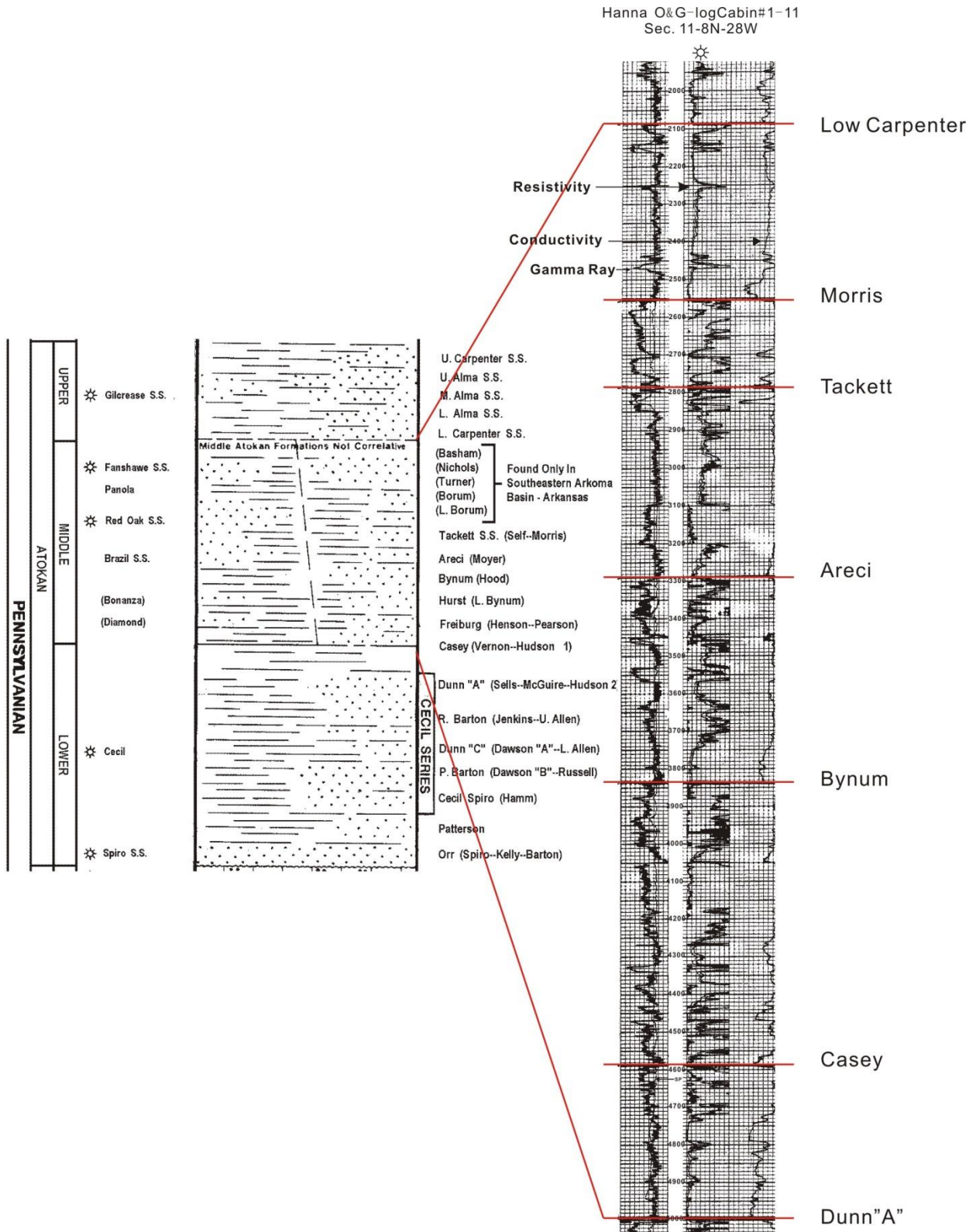


Figure 5 Stratigraphic column of the middle Atoka formation (modified from Fort Smith Geological Society, 1988)

The thickness of the upper Atoka in the south-central part of Arkoma basin ranges to 915 m (Zachry, 1983). The interval is predominately shale and thin sandstone units. Figure 6 is the QFL diagram showing grain composition of Ozark and Arkoma petrofacies. Sandstones from Atoka formation have 75 to 90 percent of quartz with very fine to fine grained and poorly to moderately rounded, 5 to 25 percent of metamorphic lithic fragments (such as slate and phyllite) and up to 8 percent of feldspar (Houseknecht, 1986). The thickness of lower Atoka ranges from 150 m near the northern margin of Arkoma Basin to 305 m in the south (Zachry, 1983). The sandstones from lower Atoka were developed four to five units separated by shale units in delta and tidal flat systems.

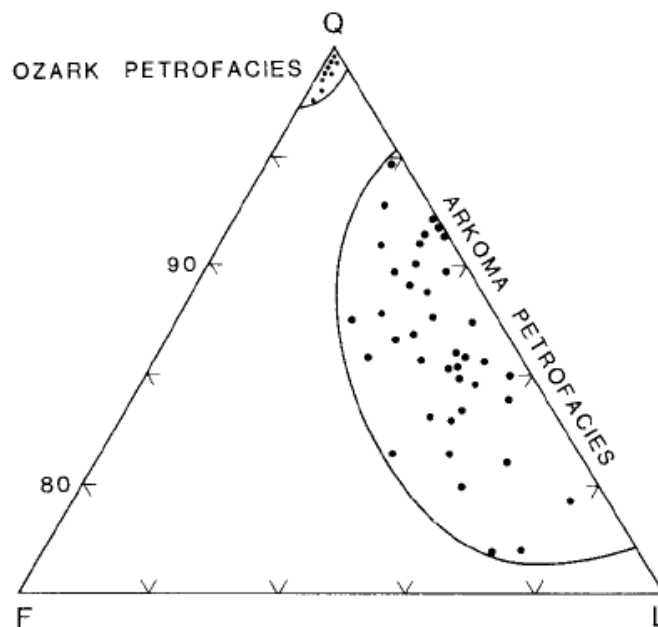


Figure 6 QFL diagram showing grain composition of Ozark and Arkoma petrofacies (Houseknecht, 1986)

1.4 Tectonic and structural history

Atoka formation of the Arkoma basin reflects the transition from sedimentation on a passive, rifted margin to sedimentation in a foreland basin. The tectonic interpretation of Ouachita orogenic belt and foreland basin is based on the consumption of oceanic crust and lithosphere collision (Houseknecht, 1986).

Rifting activity caused the expanding of ocean basin in the late Precambrian or earliest Palaeozoic (Thomas, 1977) (Figure 7A). After that, the southern margin of North America was replaced by an Atlantic type margin during the middle Palaeozoic (Figure 7B). From early Mississippian, the expanded ocean basin terminated and started to converge effected by southwards subduction (Figure 7C). In early Atokan time, the subduction activity continually impacted the residual ocean basin. The cracked continental margin of North America was obducted by the north side of subduction zone (Figure 7D). As a result, a great number of normal faults were formed by flexural bending of continental crust occurring in the foreland part. The different thickness of stratum between these normal faults that synsedimentary faults were formed during the early to the middle Atoka time. In late Atokan time, the subduction successively pushed northwards against stratum, forming a foreland basin (Figure 7E).

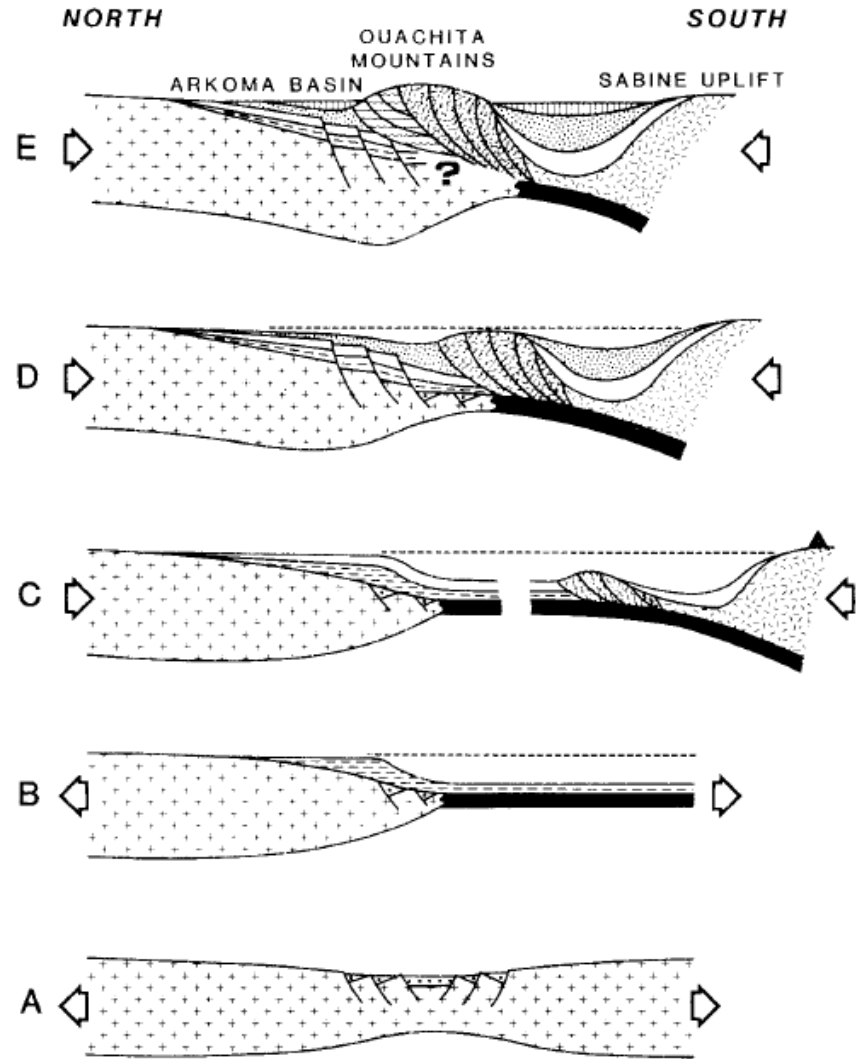


Figure 7 Cross sections showing the tectonic development of the Ouachita-Arkoma system. A: Precambrian rifting B: Late Cambrian to Early Mississippian passive margin development C: Early Mississippian to Early Pennsylvanian south-directed subduction D: Late Mississippian to Early Pennsylvanian normal faulting E: Late Pennsylvanian thrusting. Cross sections modified from Houseknecht (1986)

Alternately, another tectonic history model of the Arkoma Basin was constructed, based on seismic and gravity data (Mickus and Keller, 1992). As opposed to Houseknecht's theory, it suggests that the Sabine block docked with North America in late Paleozoic time (Permian), but no large-scale collision occurred between the North American Plate and the Sabine continental block, reflected by difference of density value (Figure 8). The thickness of the Arkoma basin is about 14

km from middle to upper Paleozoic. The sediments which include marine and nonmarine types came from the Ouachita orogeny in Pennsylvanian time. The thickness of lower Paleozoic (Cambrian- Silurian) is less than 3 km and the density of these rocks is similar to the upper crystalline crust. The sediments of Ouachita facies in the Ouachita Mountains accumulated to 15 km, and formed in deep-water environment. These sedimentary units are characterized by low-grade metamorphism with higher density reflections.

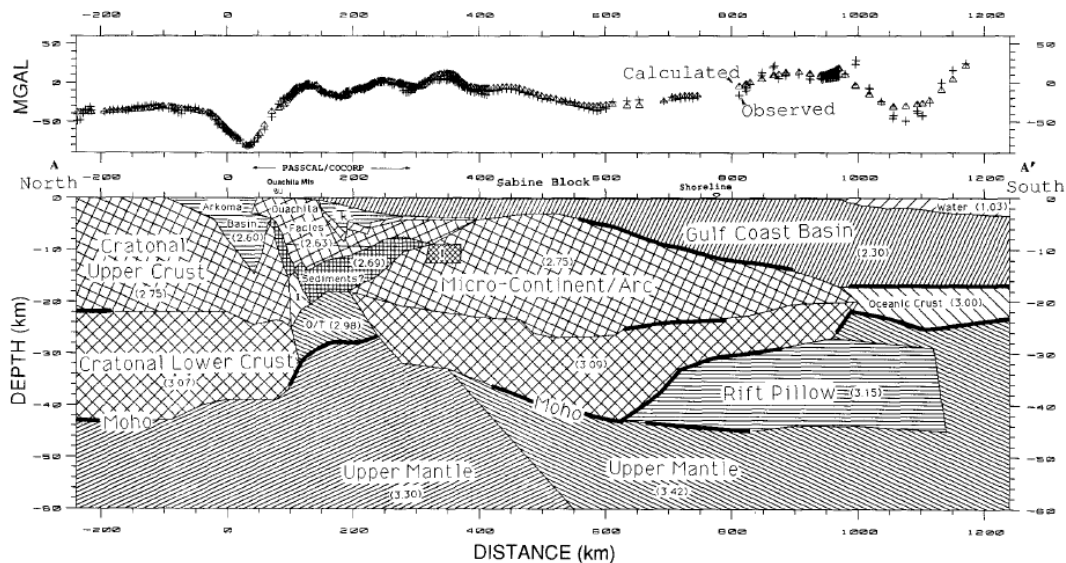


Figure 8 Lithospheric transect model. Numbers are densities in g/cm^3 . All interfaces in crust beneath area of PASSCAL-COCORP surveys are constrained primarily by seismic data. (Mickus and Keller, 1992)

1.5 Paleogeography and Depositional History

From Cambrian to early Mississippian time, shallow-water carbonates were deposited on the Arkoma shelf (Figure 9A), caused accumulation of black shales and cherts. In late Mississippian time, a thick sequence of turbidites was deposited southwestward into central

Arkansas. Submarine fans were formed due to massive accumulations of turbidites and other deep water deposits.

In Morrowan time, fluvial-deltaic facies were deposited in the northeastern part of the Arkoma Basin and shallow marine carbonate sediments were found to the northwest (Figure 9C). Slope, submarine fan and basin facies were deposited to the south reflected by deep-water quartzose clastics. The thickness of sediments increased from north to south. One of the reasons that the thickness of sediments was different is synsedimentary normal faults started to grow. On the slope area, sediments transported across the continental shelf and into the ocean formed submarine landslides. Debris flows also developed on this area causing olistostrome deposits (Link, 1986).

During the Atokan, the overthrust structure from south caused the foreland basin to contract and move northward. On the north part of the continental shelf, fluvial-deltaic, shallow-marine facies and shelf facies were mainly depositional environment (Figure 9EF). On the south part, slope, submarine fan and basin facies occurred. Meanwhile, high angle syndepositional normal faults were formed at the outer shelf edge (Link, 1986). The lower Atoka units formed thick turbidite facies in the south and thin fluvial-deltaic facies in the north. As time goes by, fluvial-deltaic depositional environment becomes majority facies during late Atoka time.

In the Desmoinesian, the foreland basin was continually impacted by advancing thrust from southern side and was restricted by the Ozark dome which was a positive lowland from northern side. As a result of these, the foreland basin closed from south to west. Fluvial, deltaic and

shallow-marine deposits were mainly formed in western Arkansas (Houseknecht and Kacena, 1984).

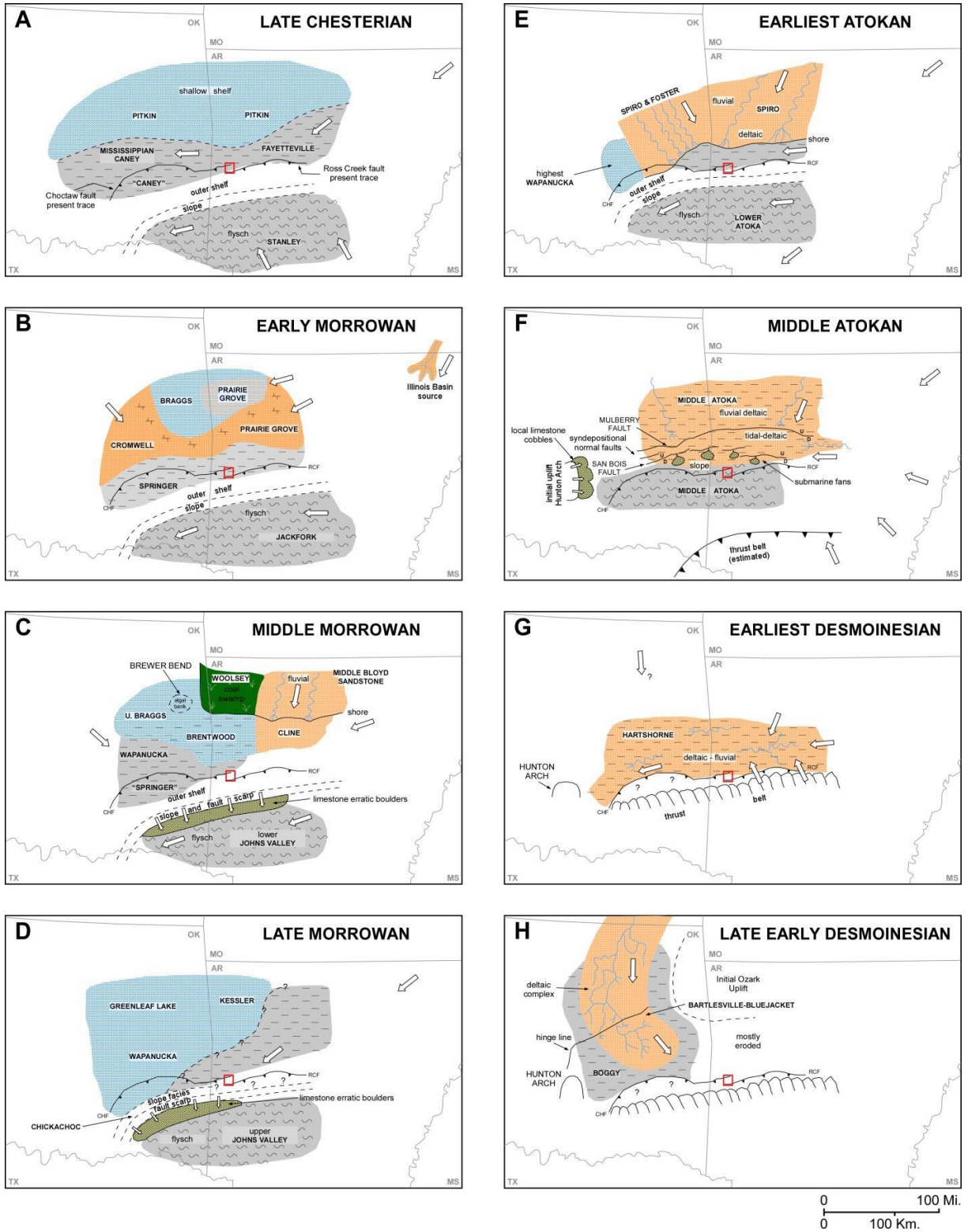


Figure 9 Paleogeographic reconstructions of Mississippian and Pennsylvanian depositional systems. Reconstructions focus on present day eastern Oklahoma and western Arkansas. Modified from Sutherland (1988).

2. METHODOLOGY

Raster logs: There are total 986 wells and 38 of them are used in cross sections, however, some of these wells were not used due to poor quality and lack of Raster Log curves. Gamma ray, Spontaneous (SP), resistivity and conductivity log are used to identify sandstone units such as Areci and Tackett, as well as the intervening shale formations. Figure 10 shows wells used to construct cross-sections and contour maps. Petra® is the main software used in data management, manipulation, visualization and integration of geological data.

Cross-section maps: Six regional index cross-sections were made. Three cross-sections stretch from north to south and three sections extend from west to east. Cross-sections which are 2D planes indicate the form and orientation of strata structure. It is used to understand the development of different strata and faults.

Isopach Mapping: Several isopach maps for target units and whole the middle Atoka are constructed to figure out differential thickness in Atokan time and support the development of the stratigraphic sequence.

Sediment Mapping: The distributions of the various types of classified sediment were mapped. Based on different shape of Gamma ray and resistivity logs, a variety of depositional models were constructed in the research area.

Stratigraphic Columns: Stratigraphic columns were constructed to show different formations and units with their thickness on the map and help understanding variation in the

depositional environment over time. They were constructed for locations along the delta or coastal area that show a wide variety of sediment and structures. These columns aid in interpreting relationships between morphology and sediment. Ultimately, the geologic processes responsible for the observed sediment distribution and structures will be interpreted.

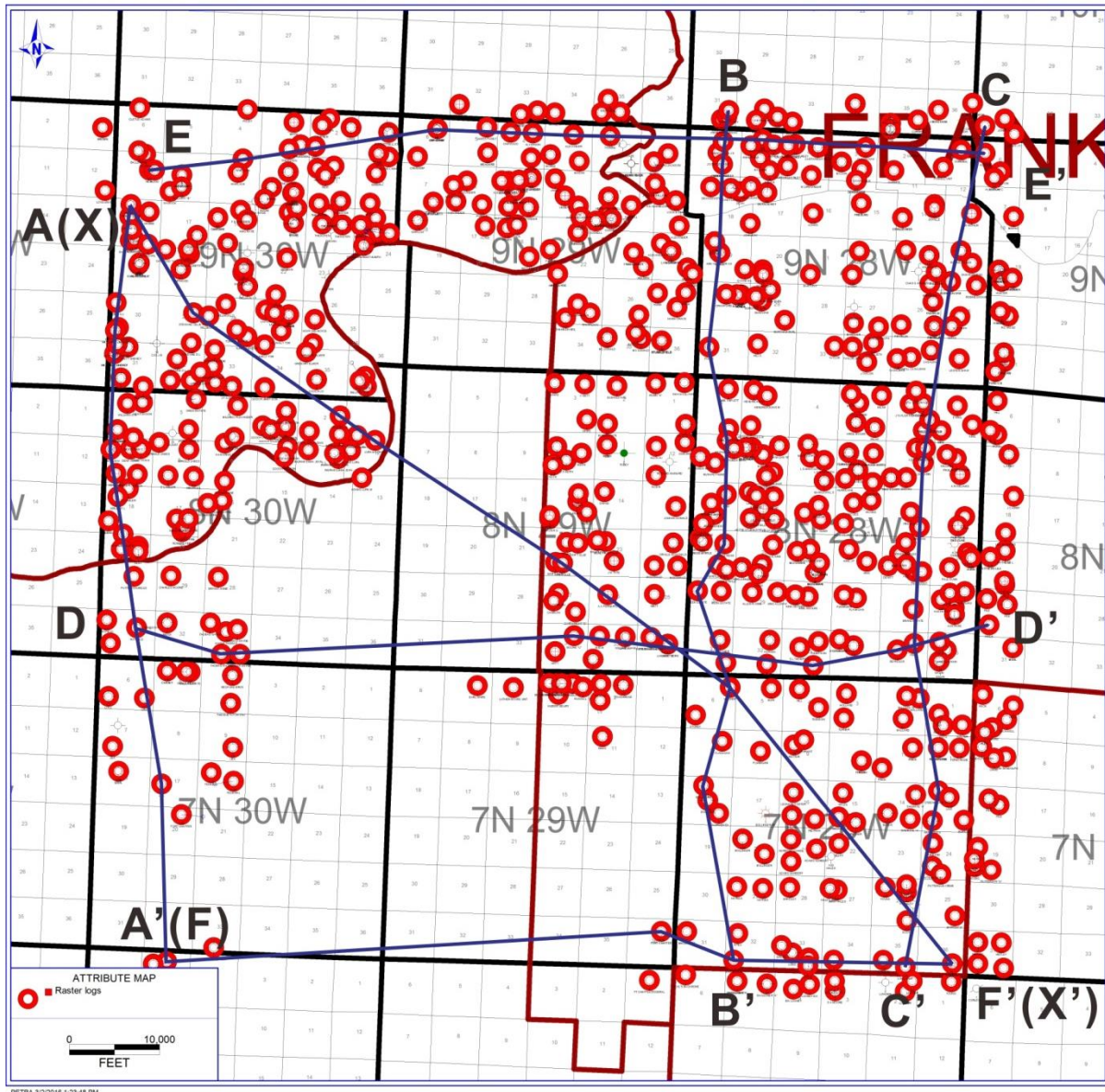


Figure 10 Map showing wells used for constructing cross-sections

3. LOG EXPRESSION

Logging techniques have rapidly improved in recent decades. Geologists are able to use specific software acquiring high resolution well log figures through internet database. Meanwhile, the highly accurate and reliable data are the basis to identify physical properties of rocks and build reasonable correlation between wells. Consequently, log analysis is commonly used to make cross-sections and classify different strata in this study. Figure 11 shows frequently used logging curve, involving SP log, Gamma ray log, resistivity log and conductivity log.

3.1 Log Analysis

SP curve also called spontaneous potential curve is one of the basic logs used in analysis. The mechanism of SP curve is measuring the difference in electromotive force between the fluid in the drilling mud and fluid in the pores of rock (North, 1985). Using SP curve is an approach to detect permeable beds, boundaries of permeable bed, determine formation-water resistivity and the volume of shale in permeable beds (Asquith and Krygowski, 2004). The value of SP curve is negative to the left and positive to the right. In the normal situation, the curve moving to the left means porous rock, such as porous sandstone. On the contrary, high positive reading indicates imporous rocks, such as dense limestones, shales and evaporates. As a result, the SP curve is an indicator to identify lithology of different rocks, and variation of porosity and pore fluid.

In addition to SP curve, gamma ray is the other useful logging method in recognizing

formation. It measures the natural radioactivity in strata and distinguishes high radioactive shale and relative low radioactive shale-free sandstones and carbonates. Although high gamma ray reading happens if clean sandstone contains potassium feldspars, micas, glauconite or uranium-rich waters (Asquith and Krygowski, 2004), the chemical composition of rock samples in the middle Atoka does not show relative large amount of thorium, potassium and uranium.

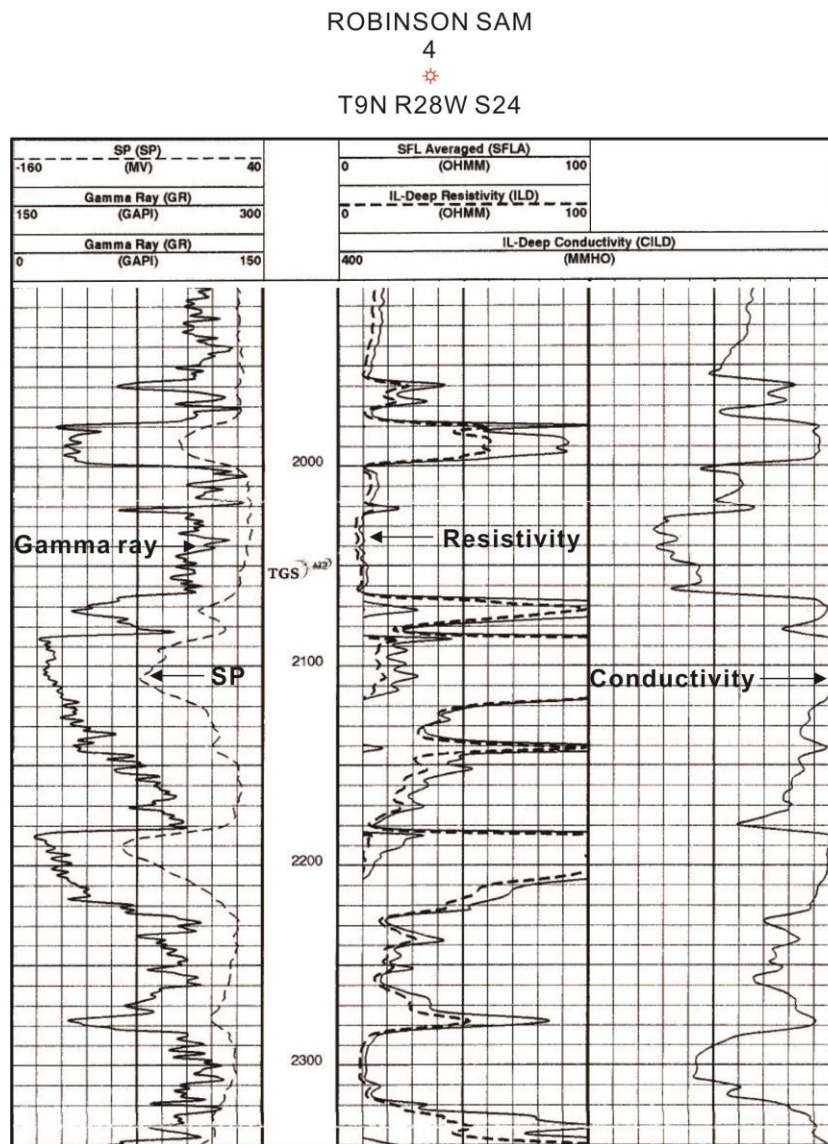


Figure 11 Combination of Gamma ray, SP, resistivity and conductivity log in a #4 Robinson Sam Well (T9N R28W S24)

The resistivity log and the conductivity log have reciprocal relationship. As for resistivity log, it is used for determining hydrocarbon-bearing versus water-bearing zones and identifying porosity and permeable zones (Asquith and Krygowski, 2004). The value of resistivity log is high in dense rocks, such as limestones, evaporates, metasedimentary rocks and porous rocks with oil or fresh water. In contrast, the low resistivity reading with high SP value generally infers shales with dispersive quartz or tight siltstones because clay is a conductor.

3.2 Facies and Log expression interpretation

Gamma ray and SP logs are generally used in log expressions of sandstone. The middle Atoka is composed of sandstone and shale units. There are four basic wireline log models reflecting different depositional facies.

The blocky or bell-shaped curves represent the successive uniform and massive sandstone and few nonsandy intervals (Figure 12). The typical depositional environments of blocky log pattern have channel-bars, fluvial channel, distributary channel, deltas and turbidity current. In particular, these sandstones are stacked one upon the other, forming sequential deposition (North, 1985). Figure 13 shows an example logging signature in T7N R28W S18 section, with a blocky pattern.

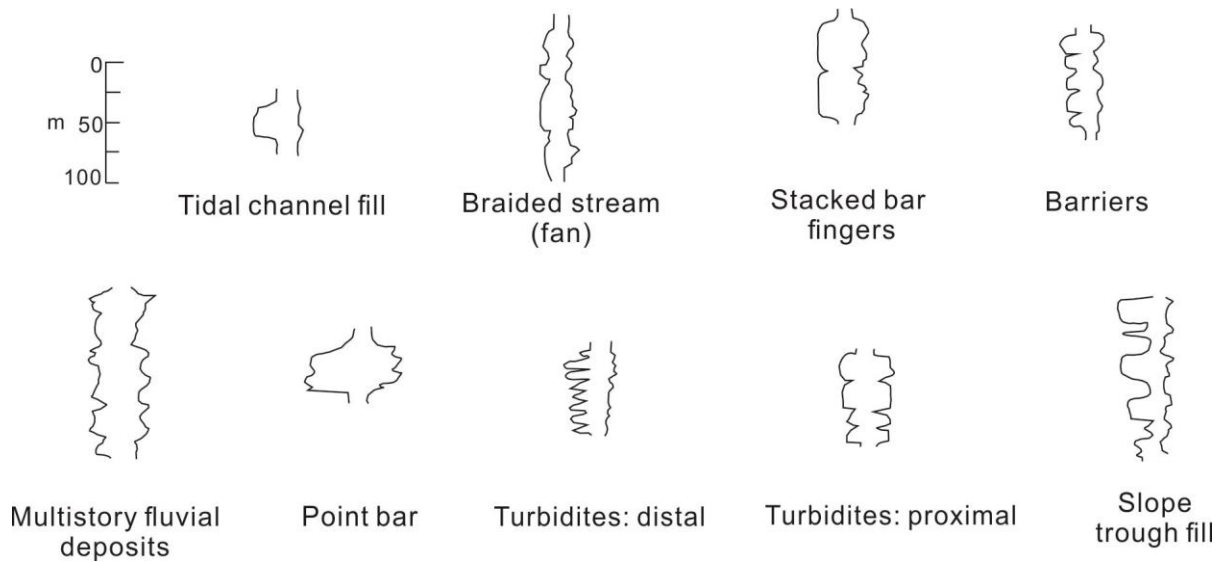


Figure 12 Schematic representation of log patterns for sand-rich depositional regimes for which the patterns are characteristically blocky in appearance. (Modified from Garcia, 1981)

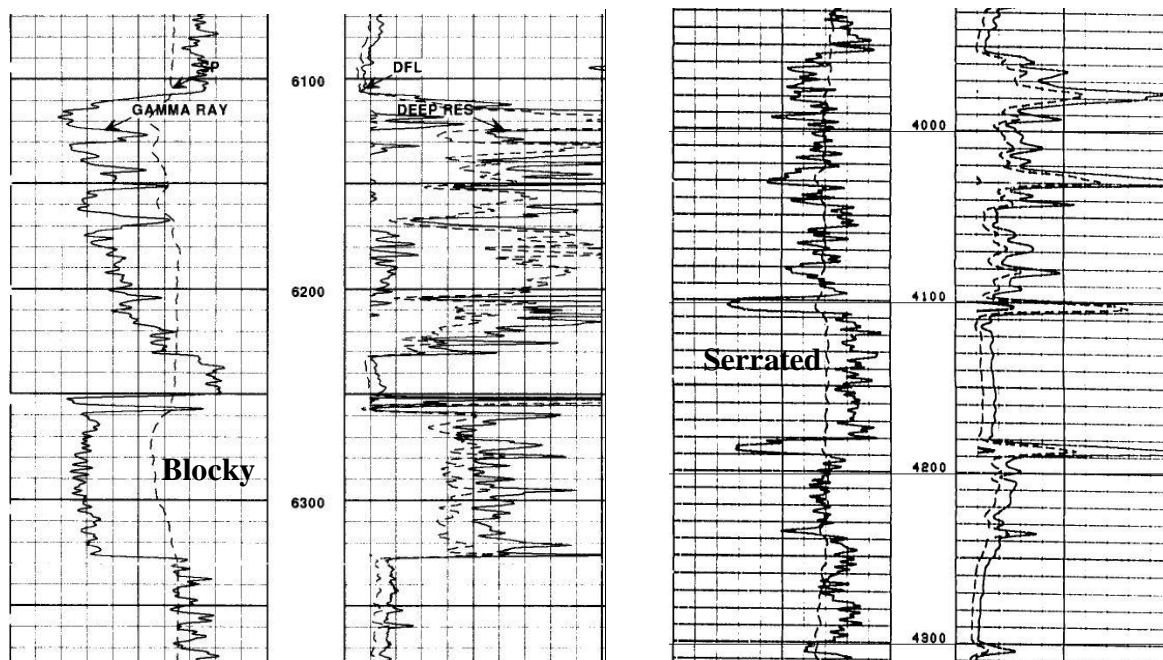


Figure 13 Presentations of blocky signature from Bollinger #1-18 located in T7N R28W S18 and serrated signature from Hatchett Lidsey #7 located in T9N R30W S30

The serrate or 'shaly' pattern infers thin thickness of sandstone separated by shale intervals (Figure 13). This pattern is characterized by lagoonal, marsh-swamp, delta-front, distal turbidites, the edges of all nonchannel, such as barrier bars and submarine fans (North, 1985).

The upward-flaring log interpretation indicates coarsen upwards sandstones (Figure 15).

In this case, bedsets become thicker. Sandstones coarsen and the sandstone/mudstone ratio increases upward (Wagoner, 1990). Sediments usually deposited in beach and barrier-bar of the upper shoreface, delta front clastic wedges, bar fingers and stream-mouth in deltas, and outer fan lobes in deep water (North, 1985).

The upward-narrowing log pattern suggests fining upwards sandstones (Figure 15).

Sandstones become finer grained and the sandstone/mudstone ratio decreases upward (Wagoner, 1990). Depositional environment commonly contains fluvial channels, point bars, alluvial fans, distributary-channel sand within delta plains, and channel turbidites leading to deep-sea fans (North, 1985).

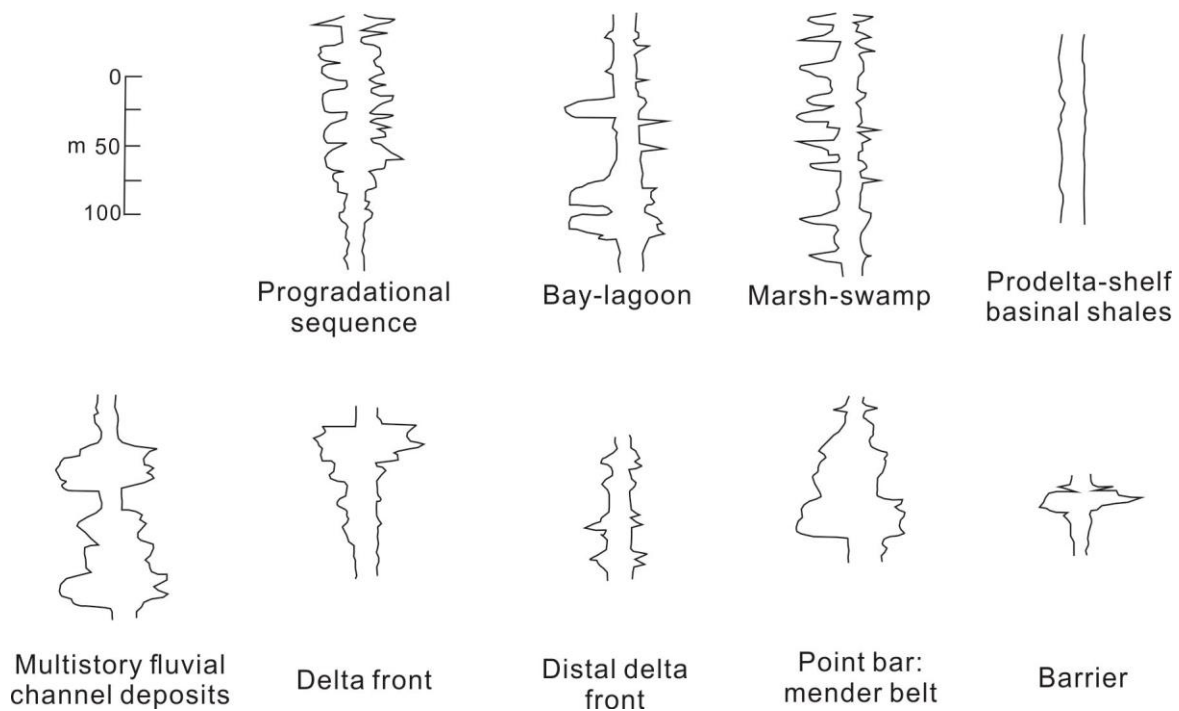


Figure 14 Schematic representation of log patterns of a variety of depositional environments in which sand-shale sequences are developed. (Modified from Garcia, 1981)

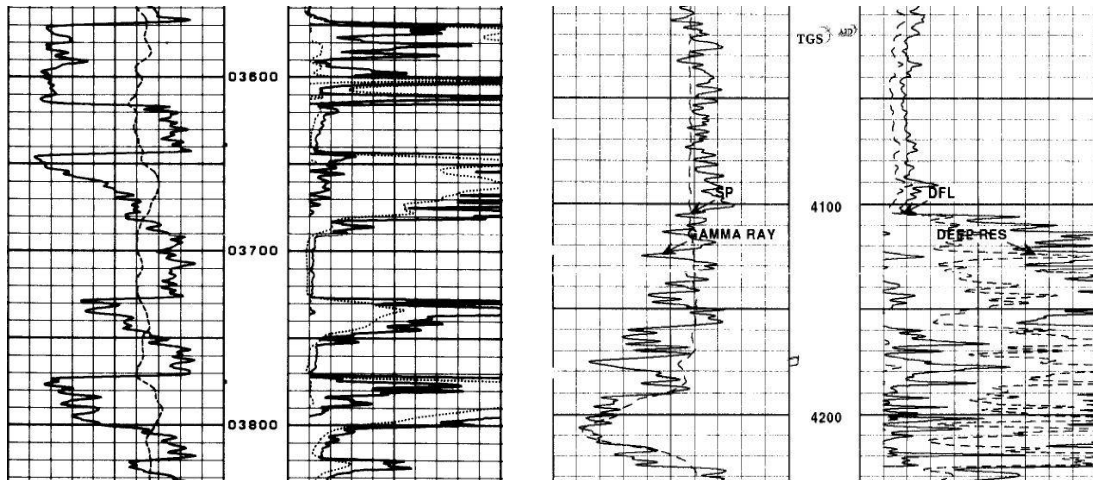


Figure 15 Presentations of upward-flaring signature from Snodgrass J S #3 located in T9N R28W S6; Upward-narrowing signature from Fisher Carty #1-31 located in T10N R28W S31

4. SEQUENCE STRATIGRAPHY

A sequence is a relatively conformable succession of related strata bounded by unconformities and their correlative conformities (Vail, et al., 1977) In general, a complete sequence includes three systems tract: lowstand, transgressive and highstand. According to relative sea-level change over time, the interplay between sediment flux and rate of accommodation restricts sedimentary succession in different stacking patterns.

4.1 Lowstand Systems Tract (LST)

Lowstand systems tract involves sediments that accumulate after the onset of a relative sea-level fall (Figure 16). It is positioned between upper transgressive surface formed when the deposits onlap onto the shelf margin and the lower sequence boundary. A forced regression means a shoreline move seaward in response to relative sea-level declining. The lowstand systems tract can be classified into an early lowstand systems tract which implies a forced regression and forms an unconformity sequence boundary when relative sea-level falls and a late lowstand systems tract which means the lowest position on the relative sea-level curve (Posamentier and Allen, 1999). However, the boundary between early Lowstand systems tract and overlying sediments is not clear if the lowstand systems tract were filled by incised valleys. Estuaries are landwards formed if the incised valleys begin to flood when relative sea-level rise, blocked dispersal of sediment onto the shelf. Lowstand systems tract ceases when the rate of

relative sea-level rise exceeds sediment supply, resulting transgression. The characteristic of lowstand systems tract in strata is an overall regressive stratigraphic unit that overlays the sequence boundary and onlaps onto the unconformable sequence boundary (Posamentier and Allen, 1999). The middle Atoka formation includes several sea-level cycles, reflecting shoreface, coastal plain or nearshore marine environment.

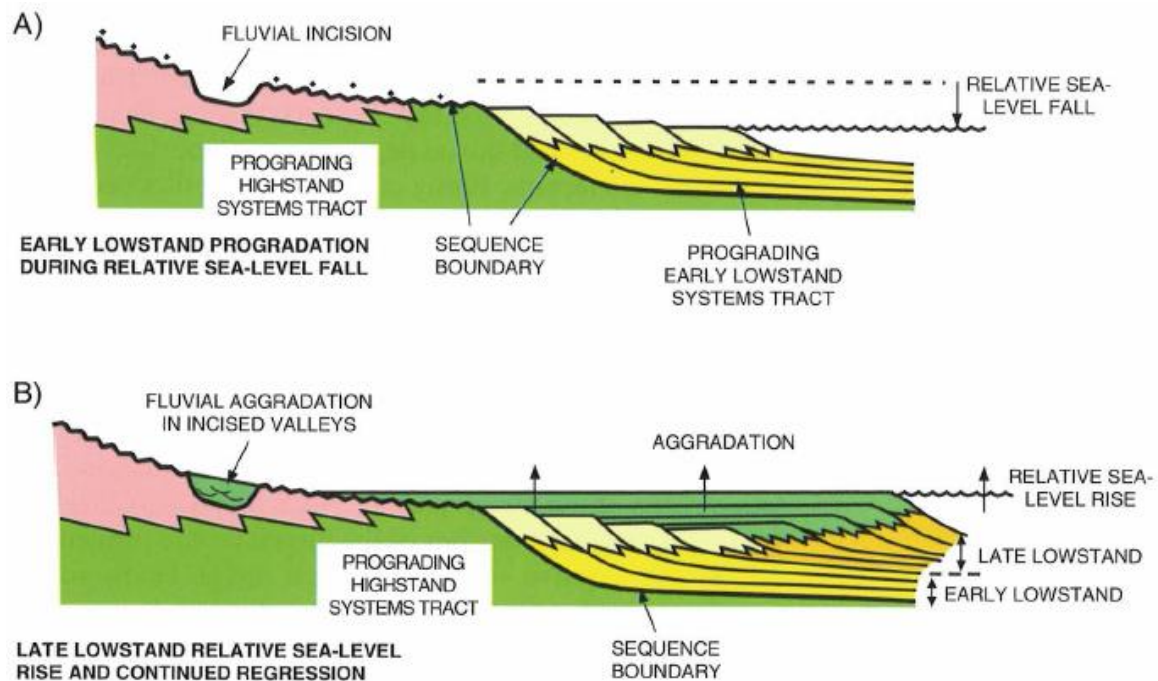


Figure 16 Schematic dip section of early and late phase lowstand systems tract and the relationship with relative sea-level. (Posamentier and Allen, 1999)

Sea-level change plays a major role determining construction of strata and location of stratigraphic boundary in coastal and shoreface environment. Through observing well log section in the middle Atoka, it is clearly shows series of successive sandstone units separated by thin shale units. For example, there are seven sandstone units divided by six shale units within 1000 feet of thickness in the lower Atoka formation (Figure 17). The thickness of the thin shale is about 30 feet per unit, indicating that higher-frequency cycles existed in early Atoka time. An

unconformity occurs at the base of the lower Atoka formation, which is the sequence boundary of lowstand systems tract. Successive sequences and associated sea-level cycles are developed in the lowstand systems tracts. Parasequences consist a stacking pattern which forms seaward progradation. As time goes by, late lowstand systems tract gradually formed from a prograding to an aggrading stacking pattern.

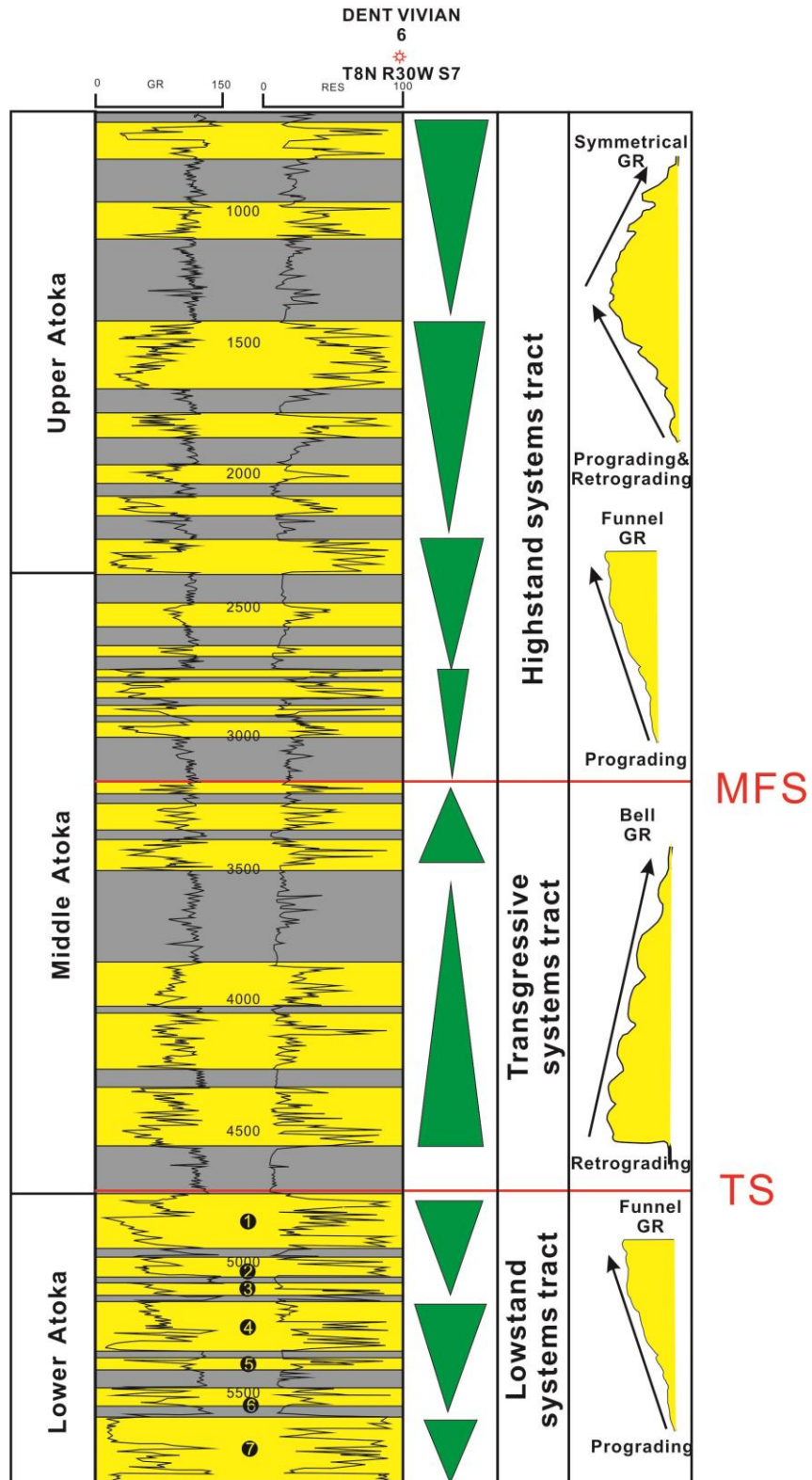


Figure 17 Example of well-log patterns in the entire Atoka formation including a lowstand systems tract, transgressive systems tract, highstand systems tract (#6, Dent Vivian)

4.2 Transgression Systems Tract (TST)

A transgression occurs when the rate of relative sea-level rise exceeds the rate of sediment input, and leads a shoreline landward migration. When relative sea-level rapidly rises, the transgression systems tract is easier to identify in coastal to shelf settings because it generally has fining-upward expression, inferring shaly sandstone or shale-rich marine sediments. The others common depositional environments involves fluvial, estuary and lagoon. The transgression systems tract can include single or a series of smaller-scale regressive-transgressive events which means a landward stepping and upward-deeping stacking pattern.

Transgressive surface (TS) is a term to describe the boundary between lowstand systems tract and transgressive system tract (Posamentier et al., 1998). It is important to note that transgressive surface which is characterized by the consolidated muds can be identified in well logs by a regressive stacking pattern, to a transgressive stacking pattern. The other boundary is defined by maximum flooding surface (MFS) which shorelines reach at the maximum landward position (Figure 18).

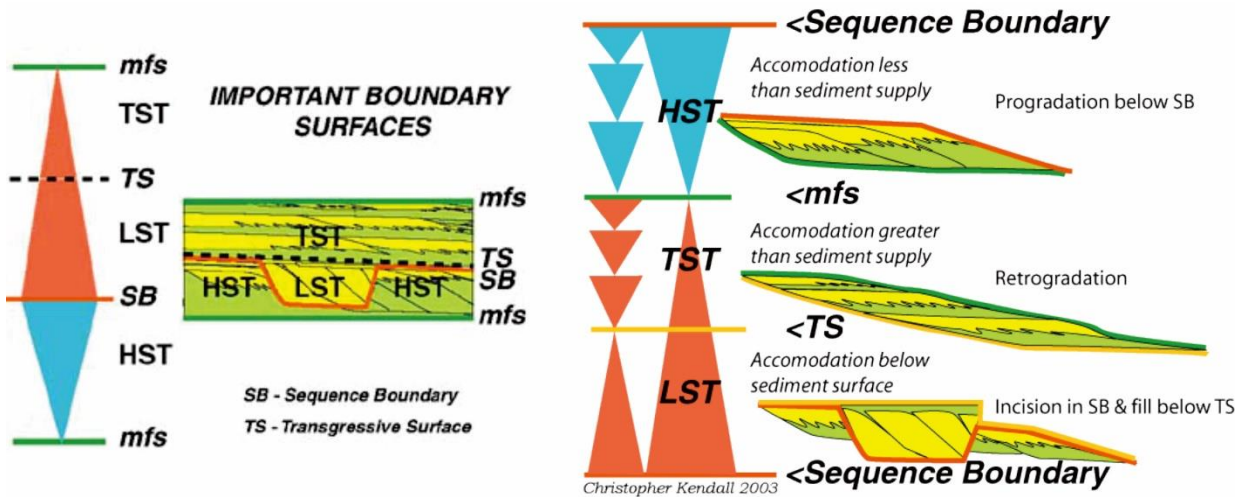


Figure 18 Schematic depiction of important boundary surfaces in systems tract (Modified from Christopher Kendall, 2003)

The cross-section from a well log in the middle Atoka formation (Figure 17) shows that coastline rapidly retreats across the shelf within a relatively short geological time because thin sandstone and shale units alternately appear in thin intervals. After that, relative sea-level continuously rise, reflected by the thick shale units. In addition, condensed section which is a thin marine stratigraphic unit formed within a slow depositional rate also occurs in the cross section, indicated by high gamma ray (Vail et al., 1984). It is a significant marker of the upper boundary of the transgressive systems tract and contains the maximum flooding surface (MFS) which is overlain by the down lapping highstand systems tract.

4.3 Highstand Systems Tract (HST)

Above maximum flooding surface, the regressive sediment deposited and constructed highstand systems tract when sediment supply exceed the rate of relative sea-level rise. It located in topographically higher setting, compared with lowstand systems tract. The lower boundary is

maximum flooding surface (MFS) and the upper boundary is defined by the basal surface of forced regression (Figure 19). The well log signature shows an upward coarsening and shallowing facies succession downlapping onto the maximum flooding surface. The sediments which come from coastal plain are composed of sandstone generally migrate seaward because the rate of sea-level rise decreases within the highstand systems tract. In the case of a more complex seaward migration of the shoreline, the stacking pattern comprises successive regressive-transgressive cycles of sediment, due to either varying rates of sediment flux or varying rates of relative sea-level rise.

In the study, located in a marine setting, the stacking pattern is regressive with a strong aggradation at the early highstand, because the relative sea-level rises rapidly and the rate of sediment influx is sufficient. On the coastal plain, high rate of sediment accommodation results in mud-dominant coastal plain deposits and coarse-grained sediments on the alluvial plain. After that, the rate of relative sea-level rises slowly so that the rate of new accumulations decreases, causing regression of the shoreline. Coastal sandstones are widely distributed and have good connection in the late highstand period. By the end of highstand systems tract, the rate of relative sea-level approaches to zero forming a progradation stacking pattern.

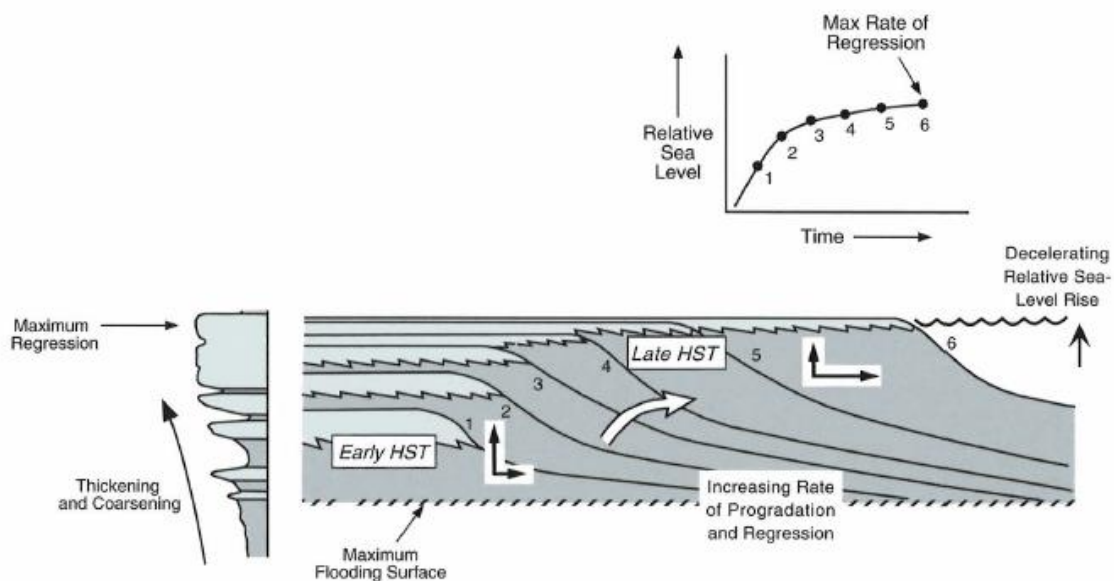


Figure 19 The stacking pattern of highstand systems tract (Posamentier and Allen, 1999)

There are some crucial factors determining these systems tracts, such as the depositional environment and type of sedimentary processes; the balance between the rate of sediment supply and accommodation; tectonic and physiographic setting; frequency of relative sea-level cycles. This study only focuses on the influence of depositional environment and high frequency of relative sea-level cycles because of limitation of data.

4.4 Sequence stratigraphy of the Middle Atoka Formation

Sequence stratigraphy study is an effective way to identify chronostratigraphic framework of repetitive, strata boundaries and their correlative conformities (Van Waggoner, 1988). Previous investigations of the Atoka formation conclude that a third order cycle exists along with the overlying Hartshorne sandstone (Valek, 1999).

1. Dunn''A''-Casey Cycle

In the northern part of study area, the middle Atoka can be divided into three cycles based on the well logs and cross-sections (Figure 20). The first Dunn''A''-Casey cycle has three major sandstone intervals and three shale units (Figure 21). The thickness of each sandstone interval ranges from 150 to 200 feet. The thick shale unit which is a mark of a bottom boundary indicates sea-level rapidly rising. Compared with the stable shale unit, the gamma ray curve frequently varies in most sandstone intervals, reflected a high level of wave energy between where sand and shale accumulate. It probably infers coastal, deltaic or tidal environment. The thickness of shale unit decrease which means relative sea-level rising slowly.

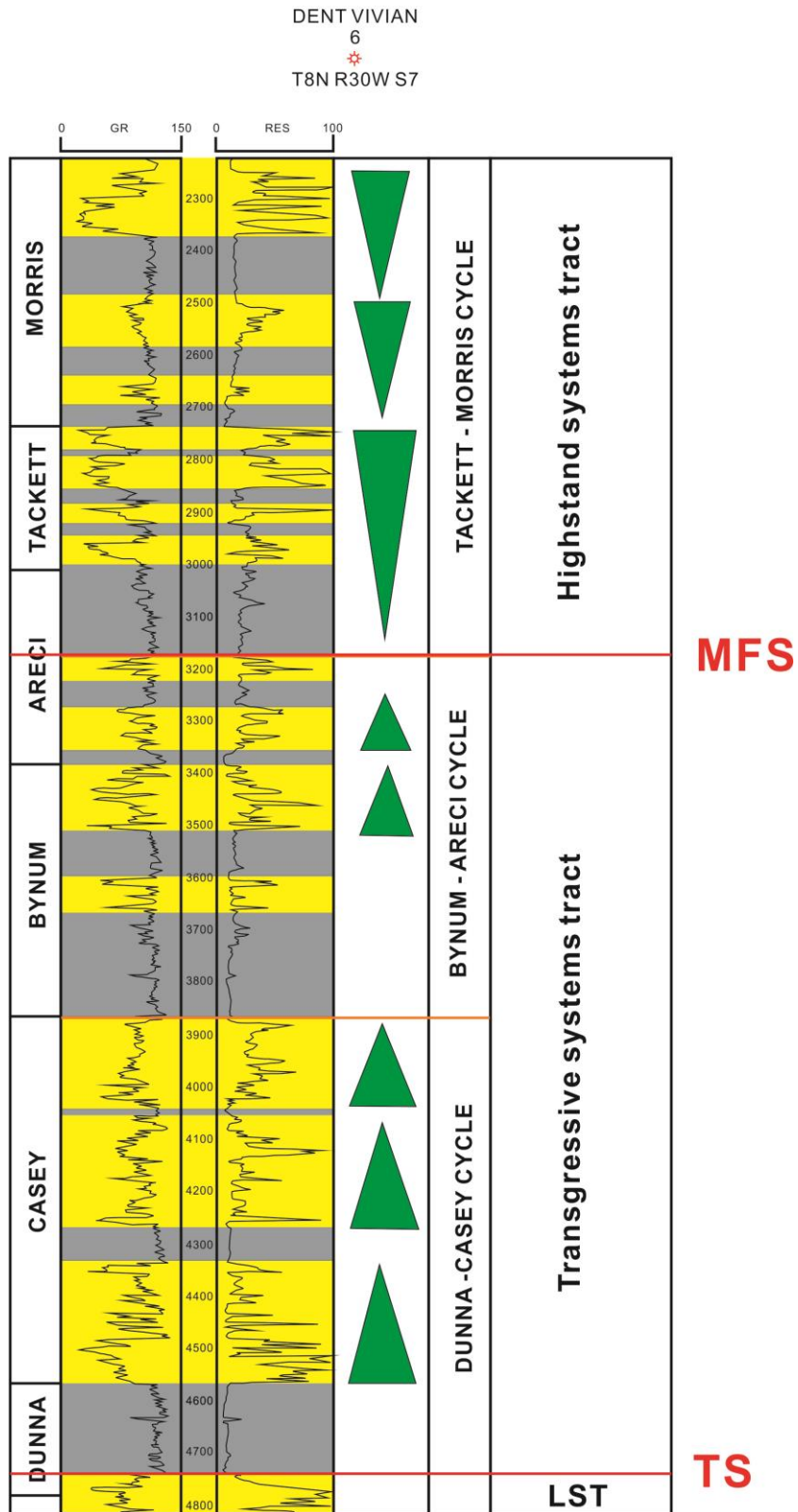


Figure 20 Example of well-log patterns in a transgressive systems tract and highstand systems tract within study area (#6, Dent Vivian)

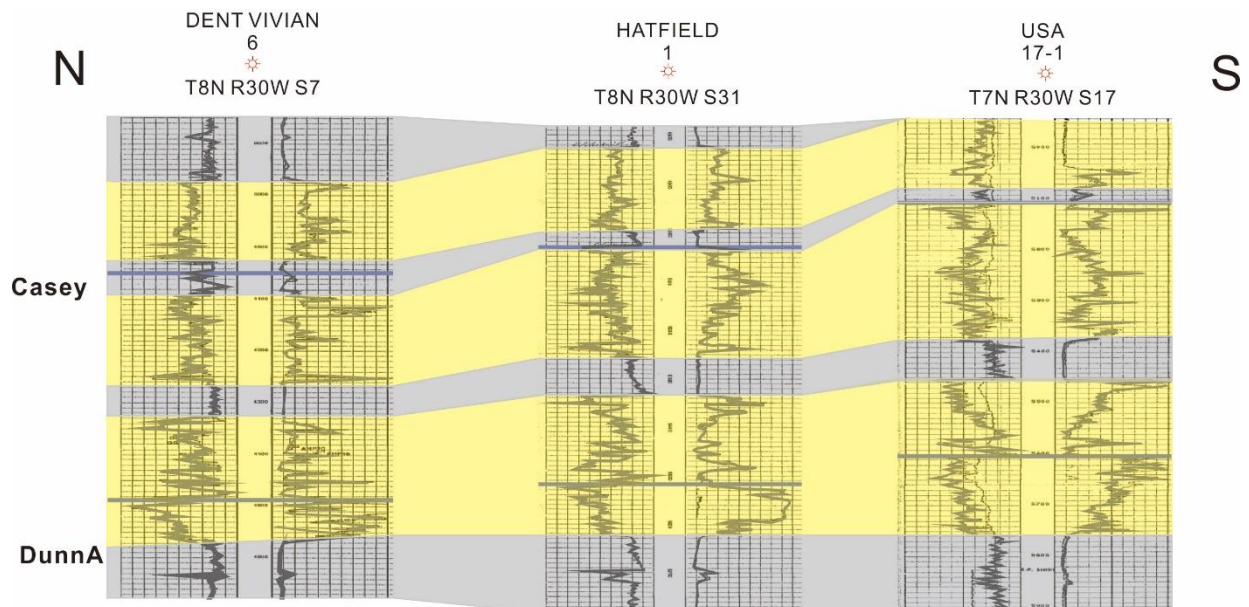


Figure 21 Selected well log from cross section A-A' shows Dunn'A'-Casey Cycle

2. Bynum-Areci Cycle

This cycle contains four sandstone intervals separated by four shale units (Figure 22).

The thickest shale unit, at the base of the boundary, reaches 200 feet. With increasing depth, the ratio of sand/mud decreases, indicating that the grain size of sandstone increases from the bottom to the top. The alternating appearing of sandstone and shale is a typical sign of coastal or shoreline environment, because transgression and regression, affected by high frequency wave. The tendency of gamma ray shows fining-upward, indicating a transgressive systems tract. From north to south, the thickness of these sandbodies increase slightly.

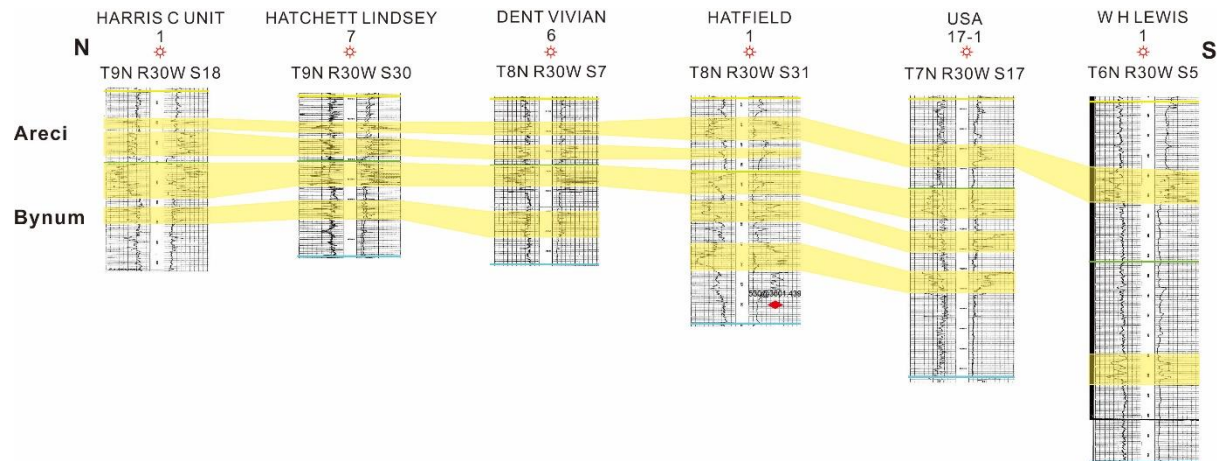


Figure 22 Selected well log from cross section A-A' shows Bynum-Areci Cycle

3. Tackett-Morris Cycle

Tackett-Morris Cycle contains two different depositional environments. Both of them have upward-coarsening features. The lower part starts from 2750 feet to 3200 feet. This parasequence reflects coastal environment, similar with Bynum-Areci cycle, because the alternative feature of sandstone and shale units. However, the upper part of this cycle is likely a deltaic environment. From 2200 feet to 2400 feet, it is possible be a distributary mouth bar associated the shape of gamma ray curve. Below 2400 feet to upper boundary of coastal parasequence, it can be explained as a delta front or prodelta environment.

5. DEPOSITIONAL ENVIRONMENT

The depositional environments experienced changes during the Atoka in the Arkoma Basin. During the early Atoka, northward transgression formed widespread Atoka sediments above an erosion surface (unconformity). The blocky sandstone intervals are recognized on the well log (Figure 17), represented pre-transgression channel systems and shorefacies. During the middle Atoka, transgressive systems tract controlled the distribution and the development of sandbodies. Periodic northward transgressions brought open-shelf environments to the Arkoma Basin, forming several thick shale units. Tidal flat coastal facies and deltaic facies are present. In addition, northeast trending normal faults were formed from south to north, so that increasing volume of sediments accumulated on the downthrown side. Upper Atoka strata are characterized by tectonic controlled depositional mode. However, periodic transgression persistently interrupted deltaic environment and generated shale units.

Several Isopach maps were constructed in order to find a pattern of the distribution of each sandbody unit, were based on the stratigraphic delineation and correlation from cross-sections. This study mainly focuses on the Tackett and Casey units because these intervals involve a complete interval. The Isopach maps reflect the variation of thickness and distribution of sandbodies in the study area.

5.1 The whole middle Atoka formation

The whole middle Atoka formation includes units from Lower Carpenter to Dunn "A". The maximum thickness reaches 4027.8 feet in section 7N 28W (southeast) and the minimum thickness is about 1878.1 feet in section 9N 30W (northwest). The average thickness is 2774.4 feet. From the figure 23, the thickness increases from northwest to southeast, and the sedimentary center located in southeastern part of study area.

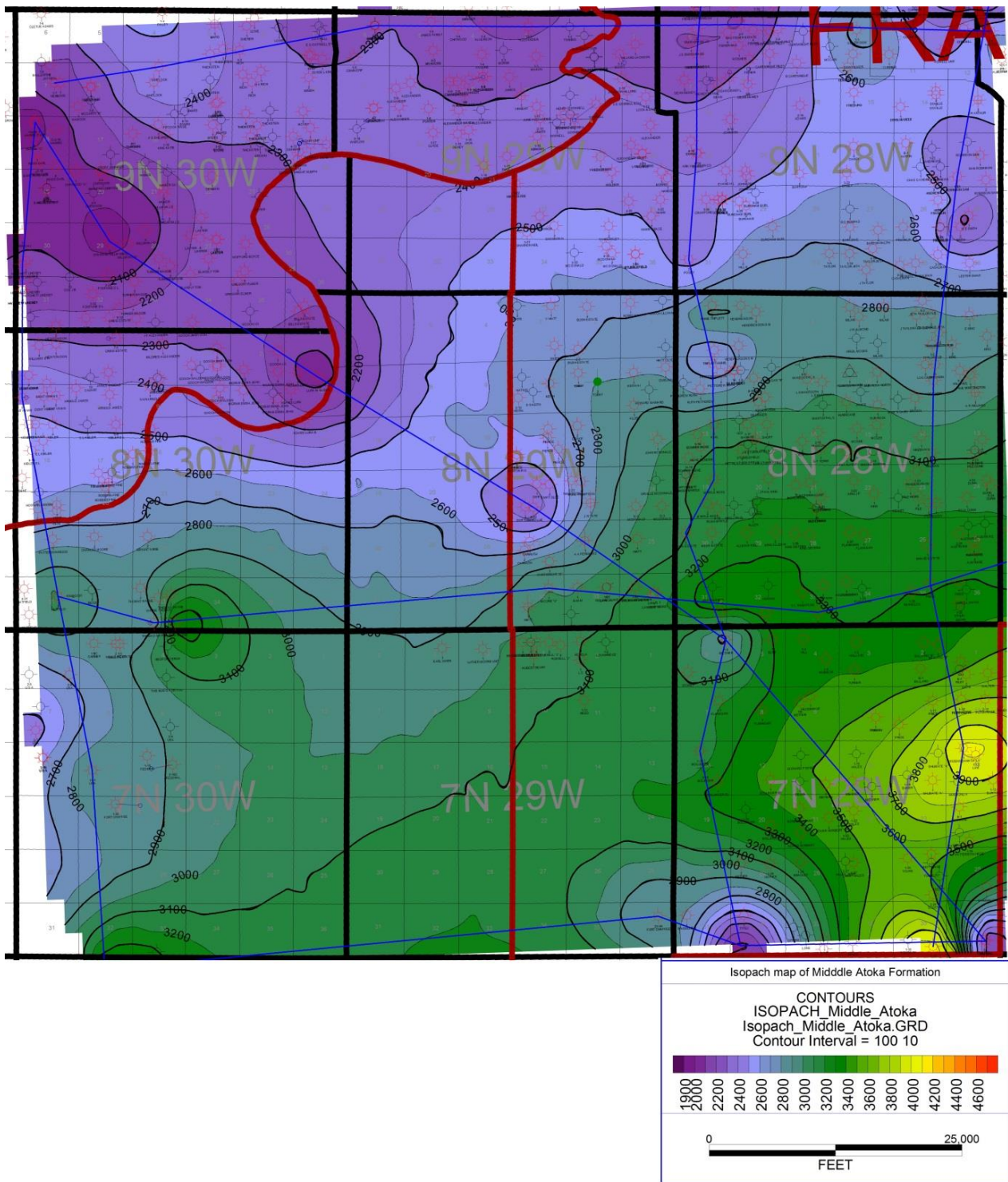


Figure 23 Isopach map of the Middle Atoka formation

5.2 Casey sandstone unit

Casey unit located at the bottom of the middle Atoka formation within transgressive systems tract. Casey sandstones are the first successive sandbodies in the whole middle Atoka formation, represented by retrogradation stacking pattern. The thickness trends of this interval increases from north to south with thinning from east to west (Figure 24). The decreasing of thickness at northwest suggests that an erosional surface at the top of Casey sandstone exists. The depositional center locates in the southeast of the study area. It reaches a maximum thickness of 1603.0 feet in section 7N 28W and the minimum thickness is about 156.4 feet in section 7N 30W. The average thickness is 643 feet.

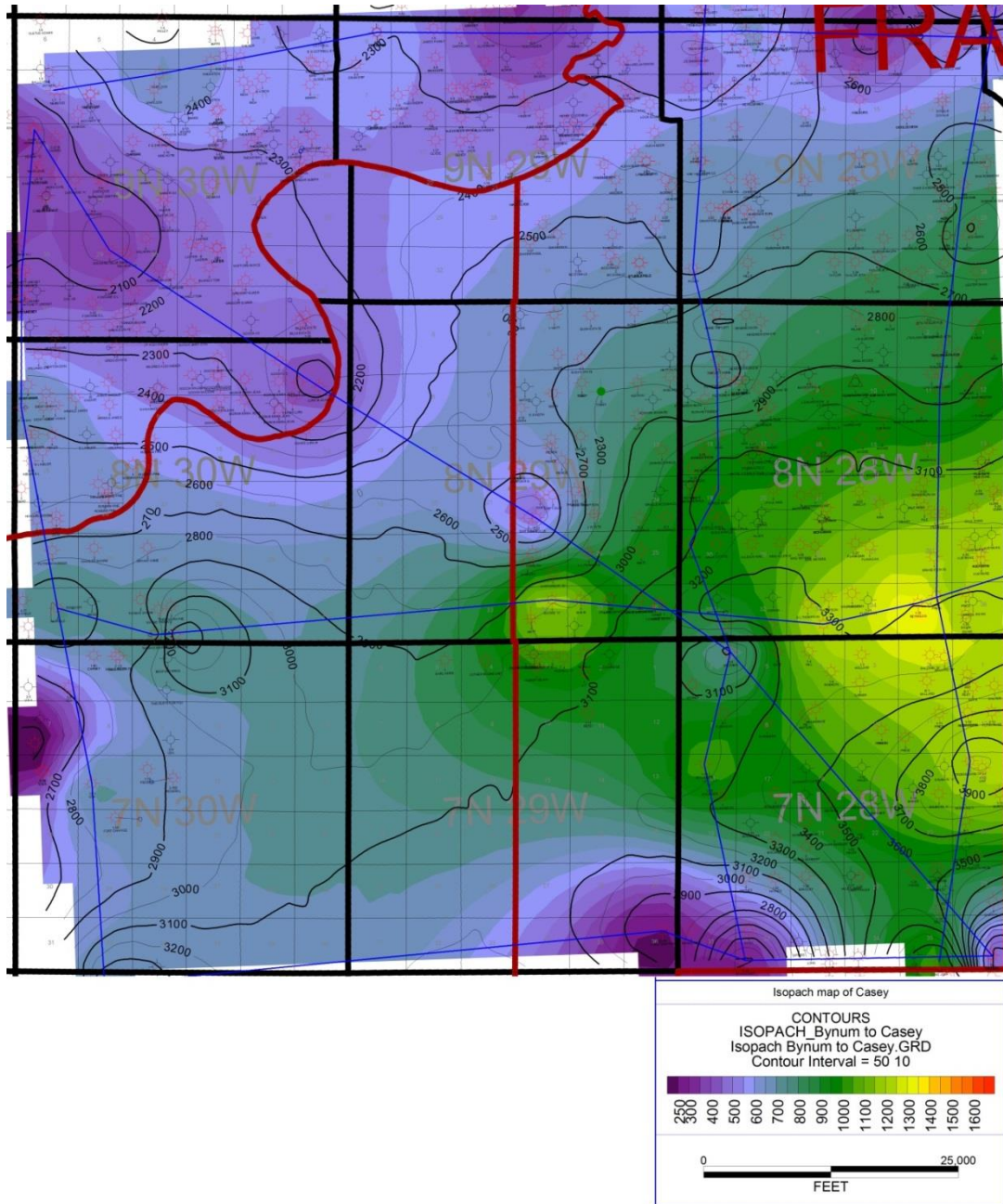


Figure 24 Isopach map of Casey unit

Shelf to shoreface successions can be divided into five cyclic facies associations: upper shoreface; proximal lower shoreface; distal lower shoreface; offshore shelf/ramp; transgressive shoreface (Farrell, 2013). Figure 25 shows a model to explain different depositional environment identified by gamma ray response.

Figure 26 and 27 show the selected well log signatures in cross section. In cross section A-A', the first well log #1 Harris C Unit shows spikes in high gamma ray values, indicating a transgressive shoreface environment which involves sediment from subtidal to intertidal located near or above the low-tide level.

Proximal lower shoreface and distal lower shoreface deposited above storm-weather wave base and they are widespread in cross-section B-B'. Both of them are featured by coarsely serrated. The blocky sandstone units near the bottom such as #6 Dent Vivian, #1 Hatfield, #17-1 USA, #1 W H Lewis in cross section A-A' are good examples.

Distal lower shoreface contains muddy sands and sand-dominated heterolithic strata with mud interbeds. The difference between proximal lower shoreface and distal lower shoreface is changing from muddy to clean sand or lack of mud interbeds. For instance, in cross section B-B', the coarsening sandstone is separated by thin mud interbeds.

Upper shoreface is defined as sediment deposited above fair-weather wave base. It is characterized by massive, poorly stratified or graded beds and blocky gamma ray response. The absence of mud is the distinction between proximal lower shoreface and upper shoreface. In the lower Atoka formation, several thick blocky sandstone units represent upper shoreface.

Offshore shelf or ramp deposited below storm-weather wave base, indicated by fining upward sawtooth pattern and high gamma ray response. It has sandy mud heterolithic strata with thin sand interbeds. Shelf commonly occurs in the middle Atoka formation and it is a significant marker to identify sea-level cycles.






Depositional Environment		Gamma Ray Log Response Patterns	Equivalent Facies
shoreface	Upper shoreface	 <p>Blocky Consistently low values of radioactivity</p>	Cross-bedded sandstone
	Proximal lower shoreface	 <p>Coarsely serrated (Coarse sawtooth) to blocky pattern Values low, or progressive shift to lower values</p>	Amalgamated hummocky and swaly cross-stratified sandstones
shelf	Distal lower shoreface and inner shelf/ramp	 <p>Coarsely serrated with superimposed finer serrations; may be asymmetrical. intermediate values; decrease in value upward</p>	Non-amalgamated hummocky cross-stratified sandstone
	Offshore shelf/ramp	 <p>Finely serrated or spikey sawtooth pattern. High values of radioactivity</p>	Interbedded rippled sandstones and bioturbated mudstones
Shoreface/ Foreshore	Transgressive shoreface/ Foreshore	 <p>Spikes in highest values of radioactivity; may be coarsely serrated</p>	Clast-supported conglomerate/ microconglomerate

Figure 25 Facies association: depositional environment associated with facies units. (Modified from Farrell, 2013)

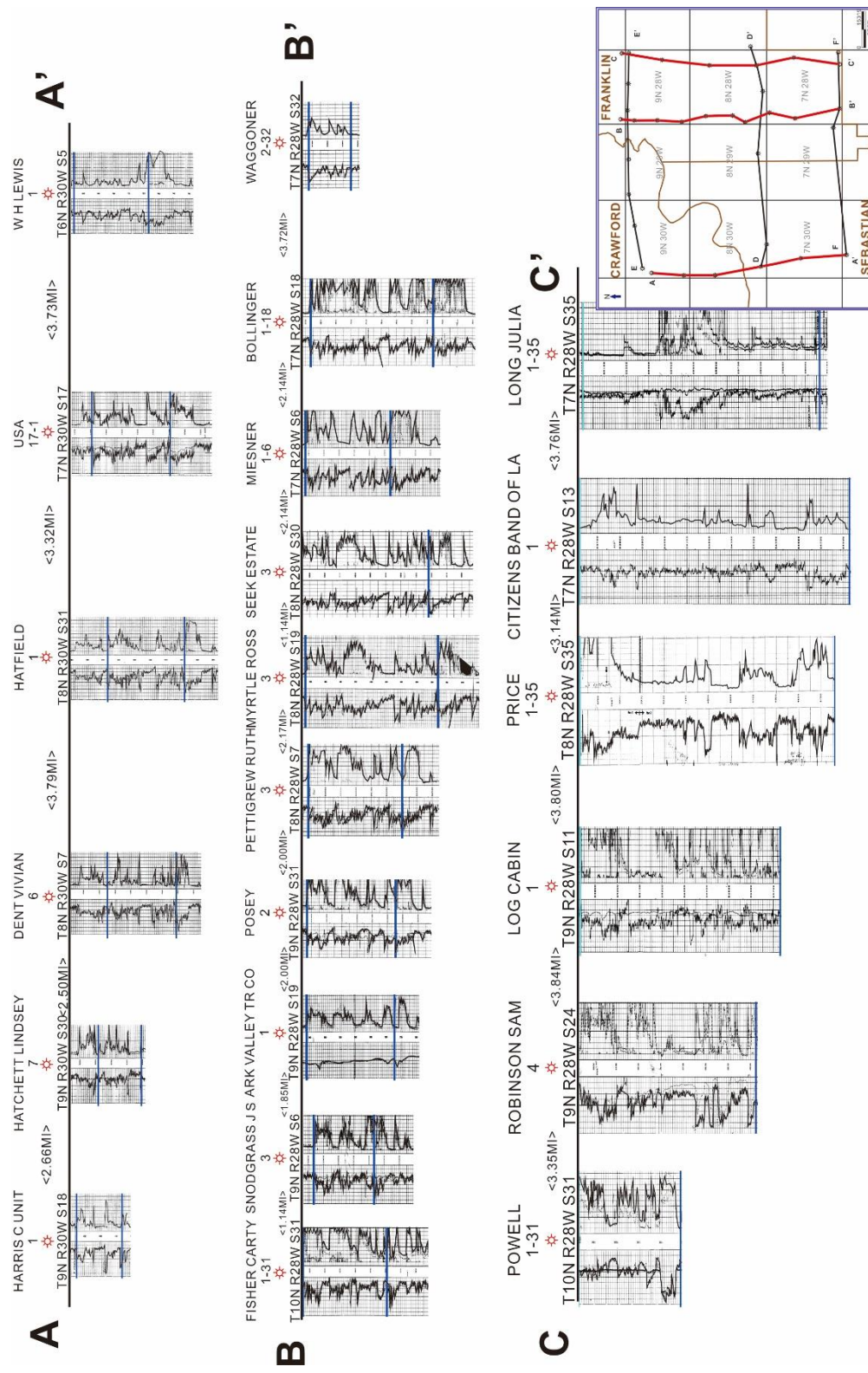
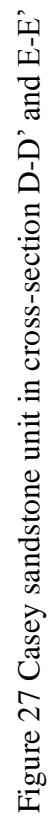


Figure 26 Casey sandstone unit in cross-section A-A', B-B' and C-C'



5.3 Tackett sandstone unit

Tackett unit composes mainly sandstone in the top of the middle Atoka. The coarsening upward consecutive sandstone units separated by thin shale intervals indicate a highstands systems tract. The maximum thickness reaches 643.9 feet in section 7N 28W and the average thickness is approximately 307.8 feet. There appear to be no obvious trend within the Tackett sandstone. The unit becomes thicker in north and southwest the main depositional center is not clear in the area (Figure 28). No large scale erosion existed at the top of the Tackett sandstone, indicating that a relative long period stable sedimentation exists before forming Tackett sandstone.

The Tackett sandstones are depicted from cross section A-A', B-B' and C-C' (Figure 29). It is clear to see the similar signature which characterized by successive coarsening upward and thin shale units. Some of them show blocky shape such as #3 Snodgrass J S and #3 Myrtle Ross in cross section B-B'; #1 Robinson Sam, #1 Log Cabin, # 1-35 Price and #1 Citizens band of LA in cross section C-C'. So the Tackett sandstones can be explained as the upper shoreface or proximal lower shoreface environment. The combination pattern of spike and serrated shape infers a transgressive shoreface.

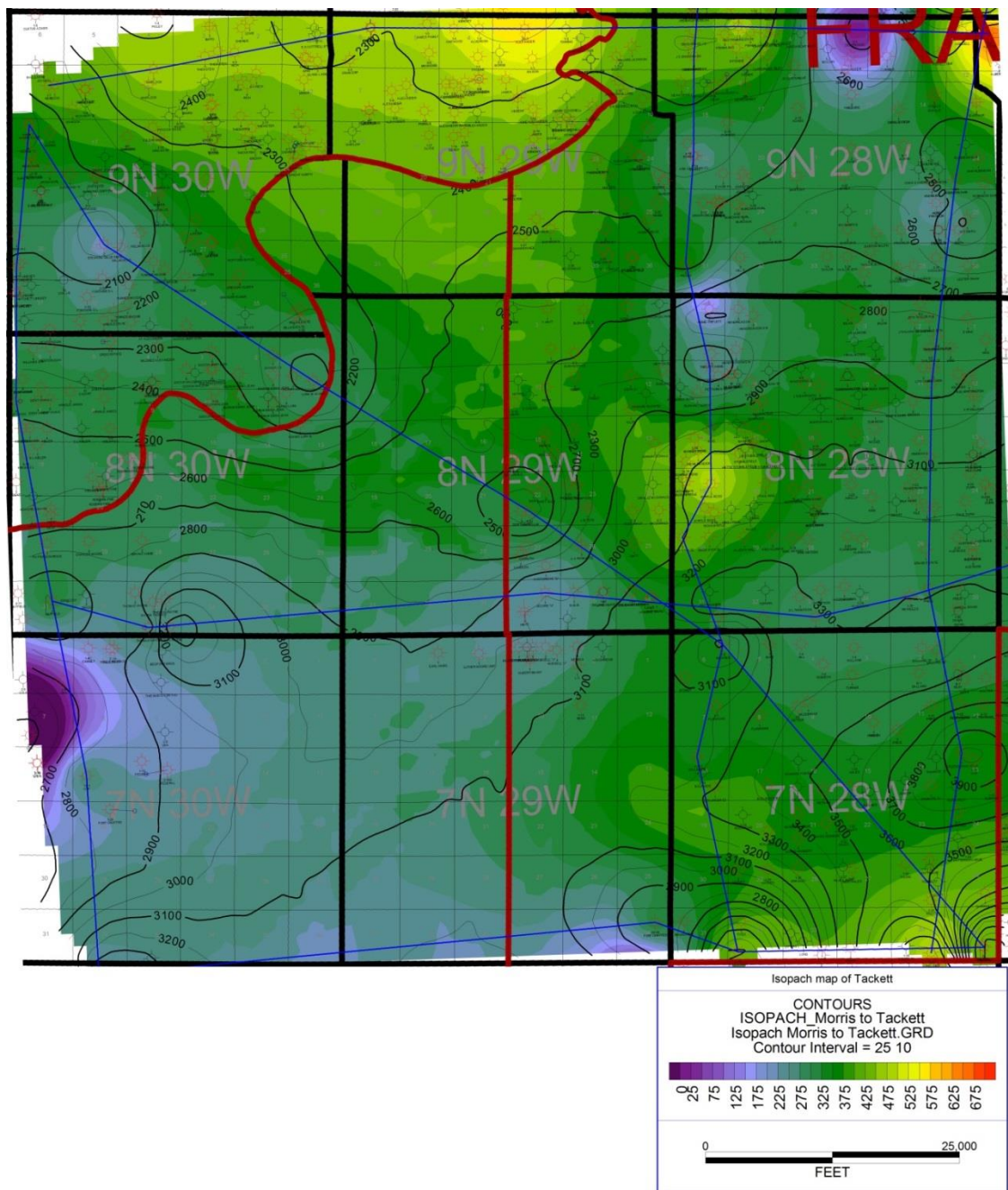


Figure 28 Isopach map of Tackett sandstone unit

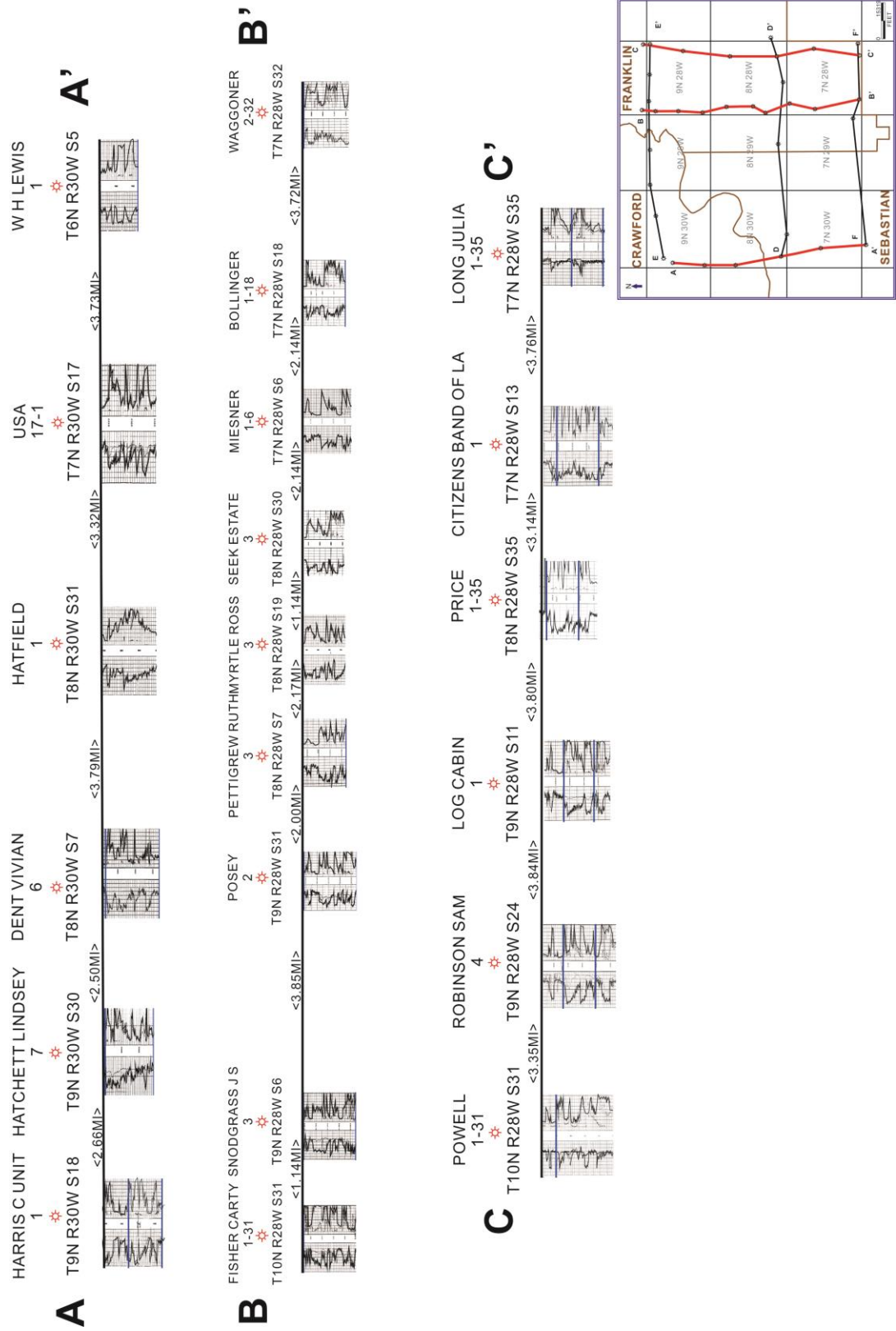


Figure 29 Tackett sandstone unit in cross-section A-A', B-B' and C-C'

5.4 Coastal settings

In a coastal setting, it is necessary to discuss wave energy and tidal energy. These two factors control the morphology of coasts and thickness of systems tract, particularly in transgressive systems tract. A coast with low wave energy and high tidal energy means recurrent sediment erosion and reworking during transgression. Estuarine-like embayment is formed including tidal channels, sand ridges, tidal flats and marshes (Posamentier and Allen, 1999). Impacted by sediment reworking, tidal currents generate a pattern described by successive fining upward transgressive systems tract.

The existence of tidal sand ridges is a key characteristic in coastal depositional environments associated with high tidal energy but low wave energy. They are formed as a combination of aggradation and progradation, identified by an hour glass shape (Figure 30). The depositional environment can be reworked offshore bars, regressive to transgressive shoreface deltas. In such settings, tidal sand ridges, tidal channels and distributary channels deposit above lowstand or highstand fluvial or coastal plain sediments. High tidal setting has influence on incised valleys during transgression (Dalrymple et al., 1994). Fluvial sediments from incised valley are overlaid by tidal estuaries and channels. The difference between these two settings is that the grain changes from coarse size in fluvial sediments to medium size in tide dominated estuarine channel-fill deposits. An example from #6 Dent Vivian well log (Figure 20), there are several thick sandstone intervals in the lower Atoka formation with low gamma ray value,

represented a transition from fluvial deposit to tidal deposit.

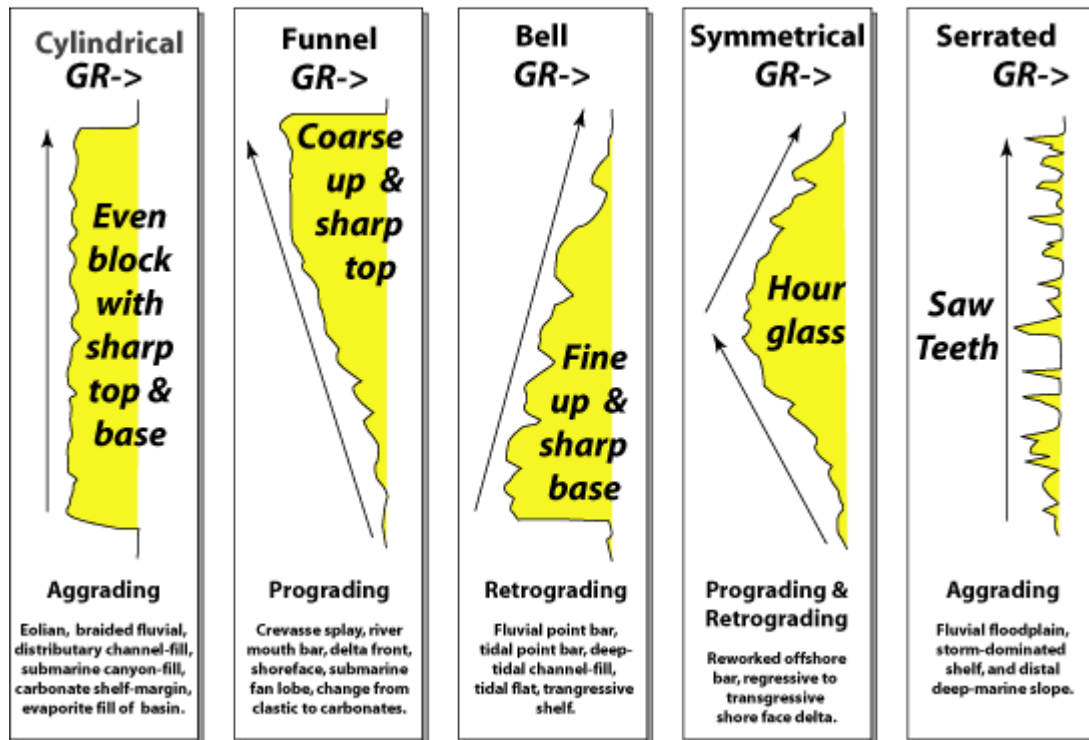


Figure 30 Gamma ray response to variation in grain size associated depositional environment (Emery, 1996)

Through observing the well log, it is obvious that the thickness of sandbodies decreases upward and sandstones become more shaley upward in transgressive systems tract because of the relative high gamma ray value. The thick shale unit is inferred to be shelf after flooding of the coastal or delta plain (Figure 30). When tidal current are not sufficiently strong to support sand ridges, other small sandbodies such as sand ribbons, sand paths can be formed. But it is extremely difficult to identify in well logs because these small sandbodies are general less than 1.6 feet thick (Posamentier and Allen, 1999).

6. CONCLUSION

The middle Atoka formation is composed of transgressive systems tract and highstand systems tract. It includes mainly three sedimentary cycles with high frequency wave. Wireline logs, sequence stacking patterns indicate deposition in coastal shoreface or nearshore marine environment. During the middle Atoka period, transgressive systems tract control the distribution and development of sandbodies. Periodic northward transgressions bring open-shelf environment to the Arkoma Basin, forming several thick shale units. Tidal flat associated coast with low wave energy and high tidal energy is present in the study area, reflected by tidal sand ridges. In addition, northeast trending normal faults were formed from south to north, so that increasing number of sediments accumulated on the downthrown.

Casey sandstone units are the first successive sandbodies in the entire middle Atoka formation, represented by retrogradation stacking pattern. It can be inferred deposition in shelf to shoreface environment. The thickness trends of this interval increases from north to south with thinning from east to west

Tackett sandstone units compose mainly sandstone in the top of the middle Atoka. The progradation stacking pattern indicates a highstand systems tract. The strata become thicker in north and southwest the mainly depositional center is not clear in the area.

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APPENDIX I : STRATIGRAPHIC CROSS SECTIONS

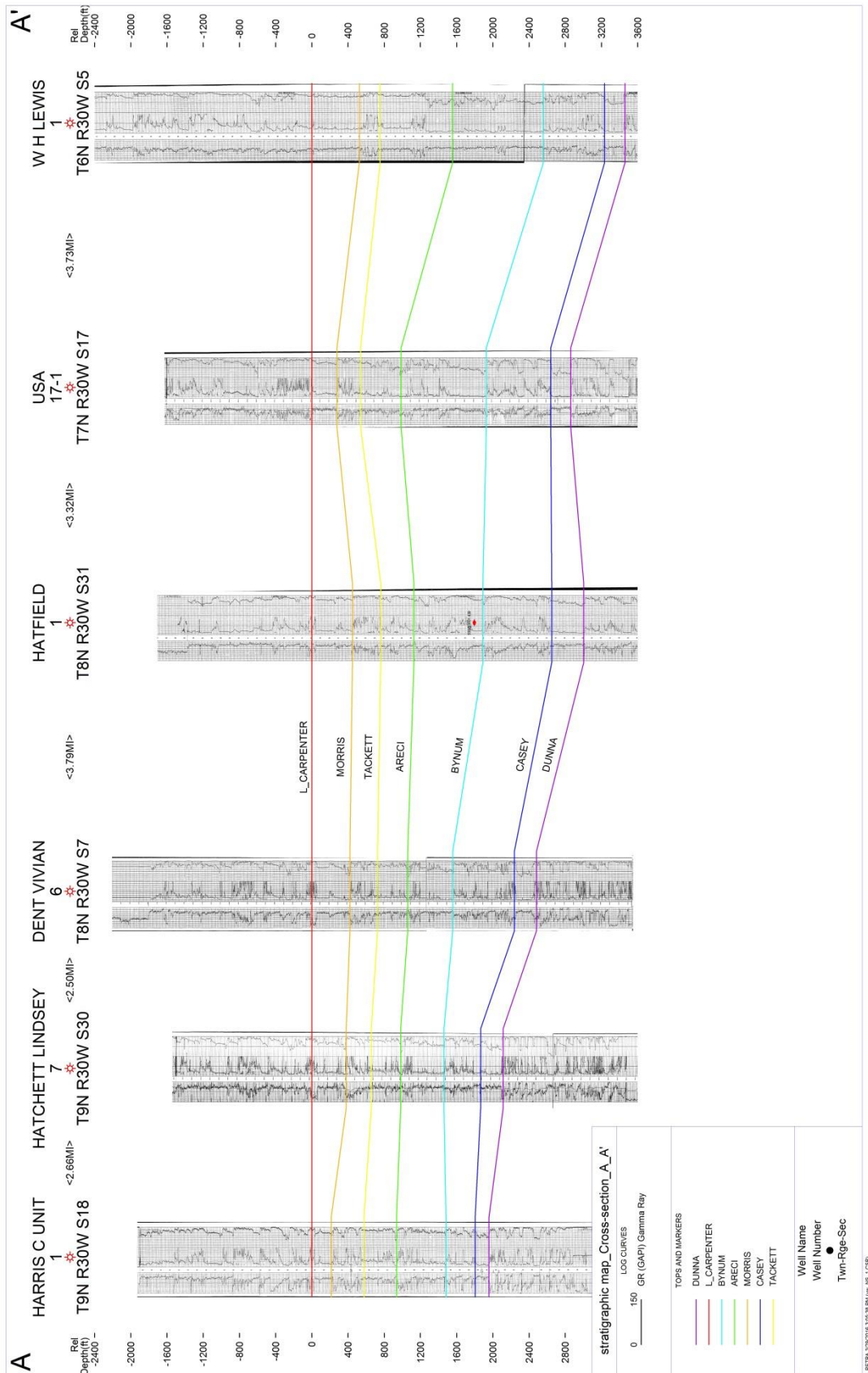
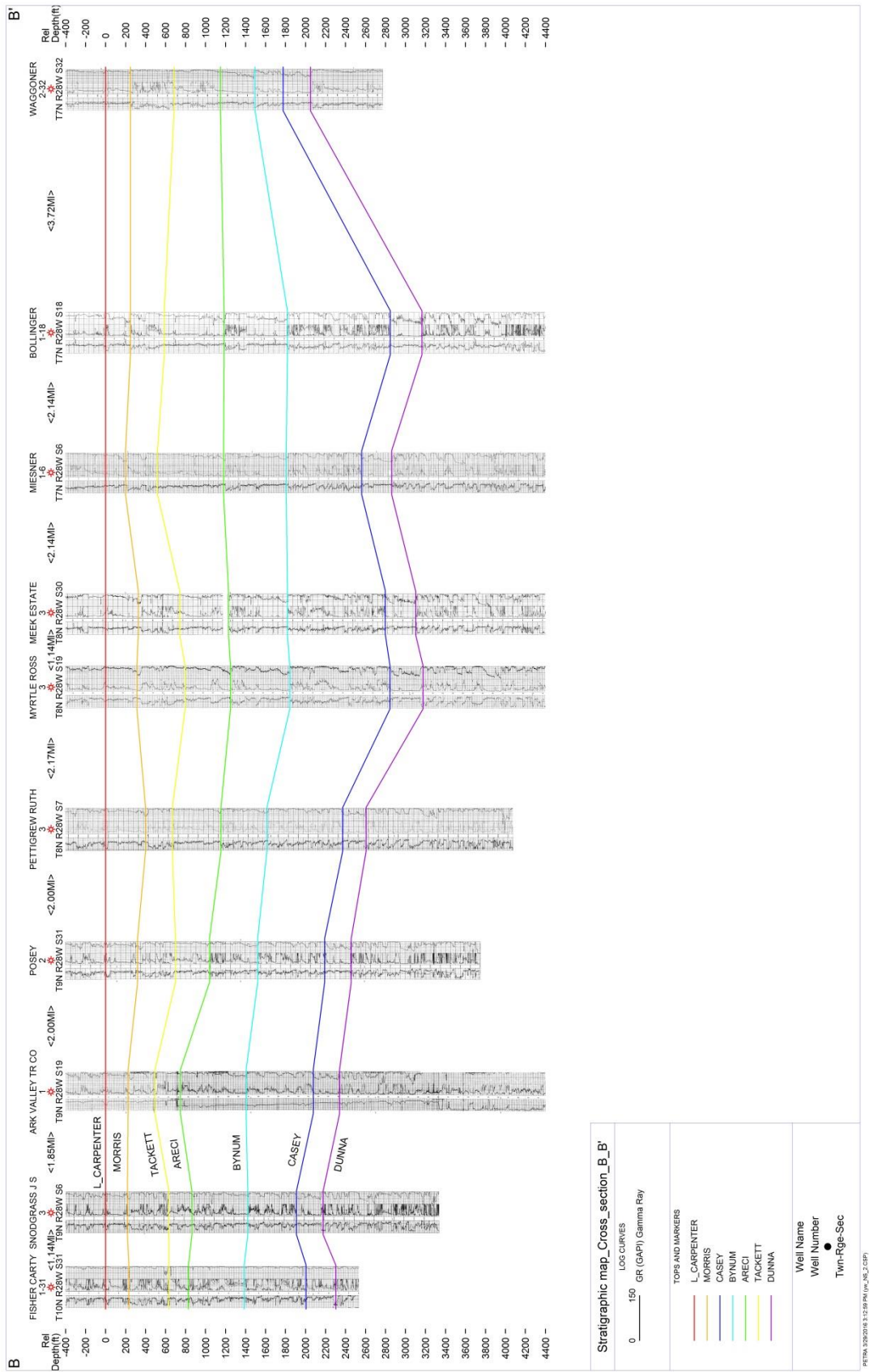


Figure 31 N-S stratigraphic cross section A-A'



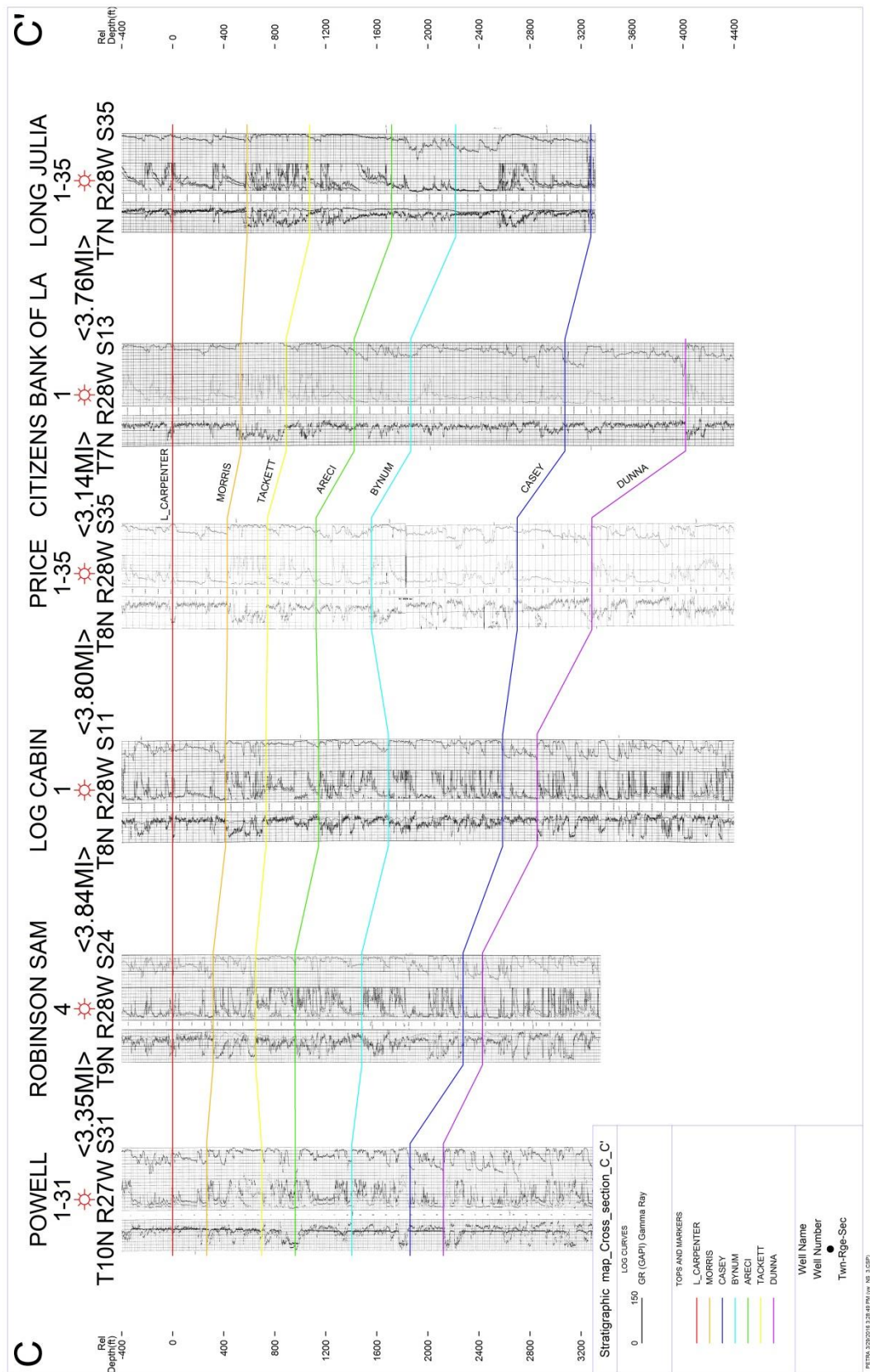


Figure 33 N-S stratigraphic cross section C-C'

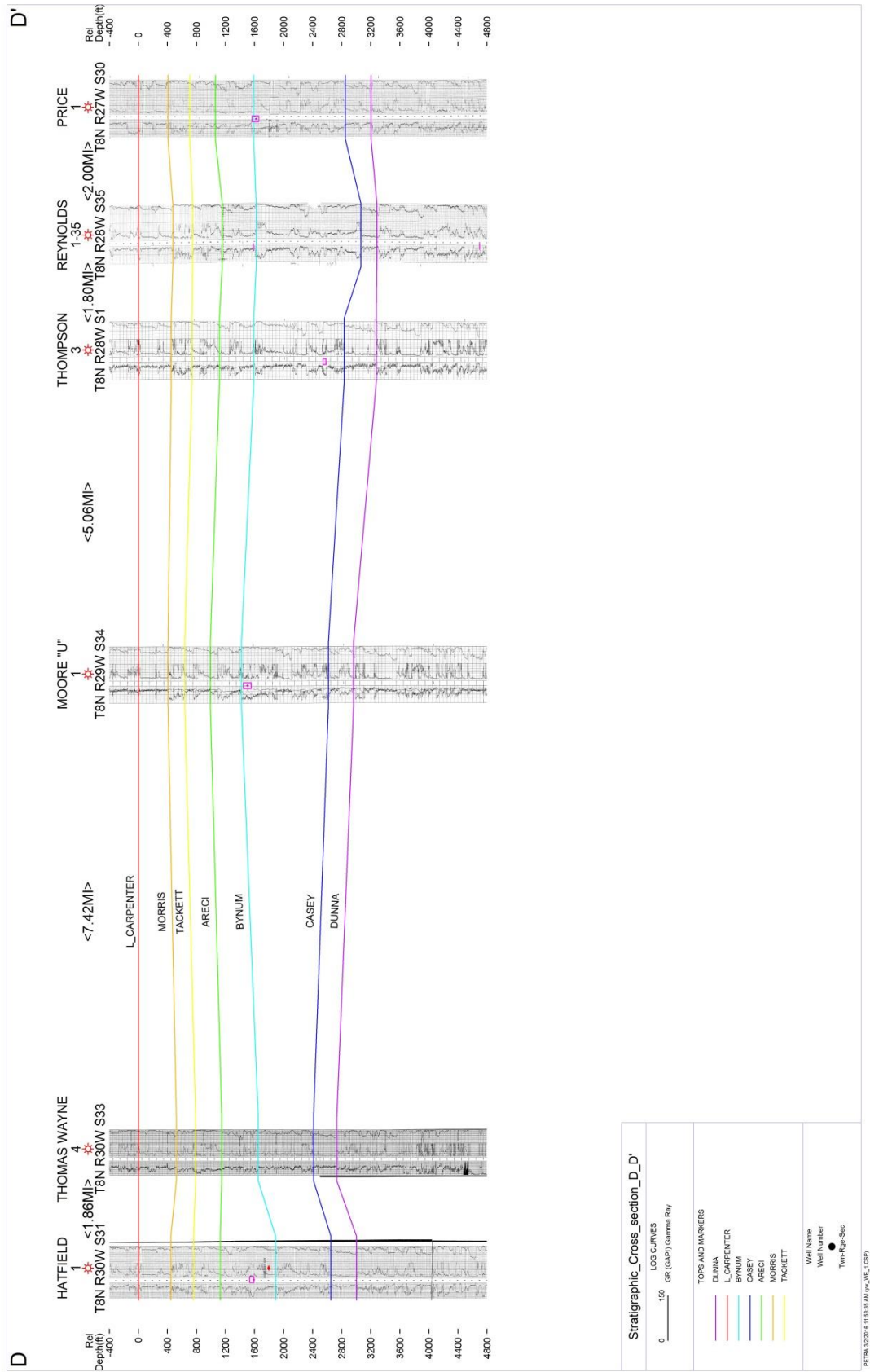


Figure 34 W-E stratigraphic cross section D-D'

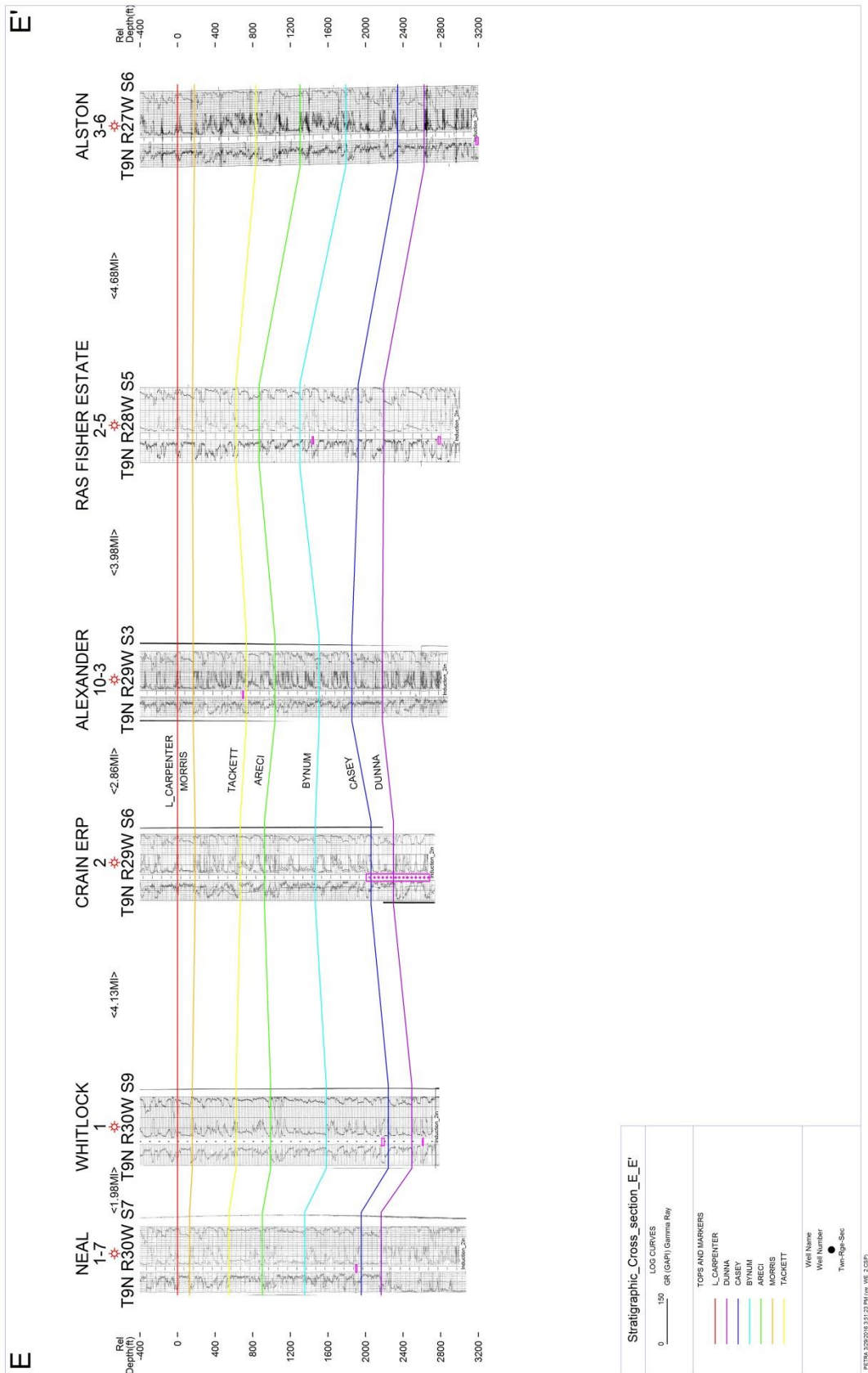


Figure 35 W-E stratigraphic cross section E-E'

APPENDIX II : LIST OF WELLS USED IN CROSS SECTIONS

Operator	API Number	Well Name
GULF OIL CORP	03033003090000	HARRIS C UNIT
STEPHENS PRDCTN CO	03033104470000	STEWARD GILLIE SMIT
STEPHENS PRDCTN CO	03033100130000	LURA M ADAMS
XTO ENERGY INC	03047112900000	SWIFT OLLIE
SAGELY FLOYD O&G CO	03047110910000	MIESNER
TXO PROD CORP	03047103760000	PHILMON
STEPHENS PRDCTN CO	03033103350000	HATCHETT LINDSEY
STEPHENS PRDCTN CO	03033105430000	DENT VIVIAN
DIAMOND SHMROCK CORP	03131100140000	HATFIELD
GETTY OIL COMPANY	03131102620000	USA
STEPHENS PRDCTN CO	03131100050000	W H LEWIS
BUTTONWOOD PET INC	03047110040000	FISHER CARTY
STEPHENS PRDCTN CO	03047107720000	SNODGRASS J S
ARK LA GAS CO ET AL	03047600310000	ARK VALLEY TR CO
ARKOMA PROD OF CA	03047104260000	POSEY
STEPHENS PRDCTN CO	03047106580000	PETTIGREW RUTH
STEPHENS PRDCTN CO	03047101010000	MYRTLE ROSS

STEPHENS PRDCTN CO	03047113380000	MEEK ESTATE
SAGELY FLOYD O&G CO	03047110910000	MIESNER
SEDNA ENERGY INC	03047112780000	BOLLINGER
TERRA RESOURCES INC	03047104900000	WAGGONER
SEECO INCORPORATED	03047101200000	POWELL
STEPHENS PRDCTN CO	03047109990000	ROBINSON SAM
HANNA OIL & GAS CO	03047104330000	LOG CABIN
REVERE CORP	03047104050000	PRICE
SEECO INCORPORATED	03047106720000	CITIZENS BANK OF LA
STEPHENS PRDCTN CO	03047103000000	LONG JULIA
IAMOND SHMROCK CORP	03131100140000	HATFIELD
STEPHENS PRDCTN CO	03131107680000	THOMAS WAYNE
TXO PROD CORP	03047104820000	MOORE "U"
ARKOMA PROD OF CA	03047104990000	THOMPSON
ARKANSAS WESTERN GAS	03047300130000	REYNOLDS
OXLEY PETROLEUM CO	03047100860000	PRICE
WILLIFORD ENERGY CO	03033101840000	NEAL
GULF OIL CORP	03033300240000	WHITLOCK
ARKOMA PROD OF CA	03033101950000	CRAIN ERP

SEECO INCORPORATED	03033104210000	ALEXANDER
STEPHENS PRDCTN CO	03047102830000	RAS FISHER ESTATE
SEAGULL MID-STH INC	03047108210000	ALSTON
STEPHENS PRDCTN CO	03131100050000	W H LEWIS
TERRY ENERGY INC	03047106370000	FORT CHAFFEE
TERRA RESOURCES INC	03047104900000	WAGGONER
TXO PROD CORP	03047103760000	PHILMON